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PSYCHOPHYSICAL TEST OF CONTRAST ACUITY TO AID OPERATIONAL EFFECTIVENESS OF AIRCREW LASER EYE PROTECTION (LEP)

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14. ABSTRACT

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Abstract

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Introduction

Acuity (seeing fine detail) is a critical visual ability, especially for the high workload, aircrew environment. All current laser eye protection (LEP) reduces acuity. In order to map out the trade-space between the protection provided by and the cost in reduced acuity incurred by a set of LEP, there must be at least one sensitive and reliable test of acuity. In order to be useful in evaluating LEP, the test(s) must be diagnostic across the multiple stimuli in the aircrew environment and must be diagnostic across the variables that have been shown to influence acuity. The following set of four experiments systematically examined multiple tests of acuity for stimuli presented on multiple media as a function of contrast, people requiring and not requiring prescriptions, stimulus motion, reduced luminance, and spectral filtering.

The best known measure of acuity is obtained with the Snellen eye chart. High contrast (black on white) letters on a paper chart are viewed at 20 feet under normal office illumination. The size of the letters is reduced from the top line to the bottom line. The smallest line that can be read by the observer is recorded. A person who can read line 8 on the chart is "normal" and has a Snellen acuity of "20/20". A person with much better than normal vision (e.g. "20/10") could read a line at 20 feet that would be readable by a person with "normal" vision at 10 feet. Legally blind for a driver's license in Texas is defined as "20/200": the person can read a line at 20 feet that would be readable by a person with "normal" vision at 200 feet. It should be noted that "normal" is a statistically lax definition. The average acuity of undergraduate students and aircrew not requiring prescriptions is much better than "20/20".

The stroke-width of a line 8 Snellen letter viewed at 20 feet is 1 min of arc. For instance, the line 8 letter E viewed at 20 feet is 5 min of arc high with three horizontal black strokes and two intermediate white strokes (each of which is 1 min of arc). The visual angle subtended by the stroke-width of the smallest line read by the observer is compared to 1 min of arc subtended by the "normal" line 8 letters in order to compute the Snellen acuity. Instead of stating the result as a Snellen acuity, it is simpler to just report the denominator (the ratio of the best line stroke-width compared to the 1 min of arc "normal"). This measure is called a Snellen equivalent and will be the metric reported in this article. Note that a Snellen equivalent of 10 is excellent, a Snellen equivalent of 20 is "normal", and a Snellen equivalent of 200 is legally blind in Texas. Measuring acuity in terms of Snellen equivalent (readable stoke-width in min. of arc X 20) permits a common metric across the stimuli used in many different tests of acuity. In addition to the letters used in the Snellen charts, three other types of stimuli are frequently used in tests of acuity: Tumbling E stimuli, gratings, and Landolt C stimuli.

The Tumbling E test was designed for children and other people not knowing the complete English alphabet (Holland, 1979). In the Tumbling E test; block, non-serif letter Es are presented in four orientations: "legs" pointing right, down, left, or up. The observer is asked to report the orientation of the "legs" and the smallest stroke-width discriminated can be converted to its Snellen equivalent.

Linear systems analysis offers a promising approach to vision. If visual acuity could be predicted by the simple summation of sensitivities to the component sinusoidal components of a stimulus, then Fourier analysis would provide an elegant model for 2D vision. Unfortunately, psychophysical evidence indicates that vision is based on edges

(e.g.; Bergen et al., 1979). While not having the linear systems advantages of sinusoidal gratings or Gabors, bar gratings appear to actually be more relevant stimuli to human vision and can be readily converted to Snellen equivalents. Similar to the Tumbling E test, the observer reports the orientation of the bar gratings. Frequently, four orientations are discriminated: two cardinal orientations (horizontal and vertical) and two obliques (upper right and upper left). It should be noted that the overall size of a Snellen E or a Tumbling E increases with stroke-width, but the size of bar grating stimuli (e.g. USAF chart and NVG charts; Ginsburg, 1984) is usually held constant in a given test. Thus the diameter of the circular bar grating stimuli remains constant, while the number of cycles decreases as stroke-width increases.

Some researchers prefer Landolt C stimuli (the fourth frequently used type of acuity stimulus) over Snellen letters (Bondarko & Danilova, 1997). As with Snellen letters and Tumbling E stimuli, the stimulus size increases with stroke-width; the circle diameter is always 5 times the stroke-width. The observer must discriminate in which of the eight directions a square gap (equal to one stroke-width on a side) occurs. There are 4 cardinal directions (top, right, bottom, and left) and 4 diagonal directions (upper right, lower right, lower left, and upper left). When the gap is on the right side, the stimulus is a "C". It should be noted that the identification of Snellen letters can be influenced by top-down processes interacting with partial information (e.g., only knowing that there was a vertical line, a diagonal line or a closed curve was present in the letter). On the other hand, the last three types of stimuli are forced-choice tasks (4AFC for the Tumbling E and bar grating tasks, but 8AFC for the Landolt C task). In contrast to using letters, using forced-choice tasks should better equate guessing rate and should be more likely to be mainly driven by bottom-up processes.

The last type of stimulus set was designed based upon the current media used to measure acuity and used to present information to aircrew. While acuity tests were originally presented on paper, many acuity measurements are currently generated by computer on either a CRT or LCD display. Similarly, the use of CRT and LCD displays is increasing in modern cockpits. In both CRT and LCD displays, the pixel array cleanly depicts vertical and horizontal lines, but diagonals and curves contain "jaggies" due to aliasing (Hoffman, 1997; Bach, 2003). Due to the physical constraints of the CRT and LCD displays, it is to be expected that acuity for the cardinal directions of the bar gratings (vertical and horizontal) will surpass the acuity for the diagonal bar gratings. The pixel array of any CRT or LCD similarly makes the use of the word "circle" to describe the pre-gap template for a Landolt C stimulus a misnomer. A two-pixel stroke-width "circle" is actually an octagon. Consequently a set of Landolt octagons was constructed with gaps at the four cardinal sides (top, right, bottom, and left) and at the four diagonal sides. Compared to stimuli printed on paper, CRT and LCD monitors may differ in the acuity afforded for cardinal and diagonal Landolt octagons.

In addition to investigating acuity differences between tasks (letter, Tumbling E, grating, Landolt C, and Landolt octagon) and differences between media (paper, CRT, and LCD), these experiments incorporated three classic variables influencing acuity. The first (stimulus contrast) was included in all four experiments. The Snellen letter chart uses high contrast (black on white) stimuli. The Weber contrast for Snellen letters is 96%. Regan (Regan & Neima, 1983) created a set of five letter charts that differ in contrast (96%, 50%, 25%, 11%, and 4%). He reports that measuring contrast acuity

(acuity across the multiple contrasts) can provide earlier diagnoses of some visual disorders than only measuring high contrast acuity (Regan, 2000). Other examples of clinical tests using high and low contrast letter charts include the Bailey-Lovie (Bailey & Lovie, 1976) and the Pelli-Robson (Pelli, Robson, & Wilkins, 1988). Similarly the Functional Acuity Contrast Test (Ginsburg, 1984) includes sine-wave gratings of five spatial frequencies and nine contrasts. It should be noted that measuring contrast acuity is essentially the inverse of the classic psychophysical measurement of contrast sensitivity. Contrast acuity involves the experimenter choosing a set of contrasts and measuring the observer's best acuity (highest visible spatial frequency) for each of those contrasts. Contrast sensitivity involves the experimenter choosing a set of spatial frequencies and measuring the observer's contrast sensitivity (lowest visible contrast) for each of those spatial frequencies.

The importance of measuring contrast sensitivity is well documented (e.g.; Wandell, 1995; Barten, 1999) as is its relationship to contrast acuity (e.g.; Regan, 1991; Anderson & Thibos, 1999). Changes in the contrast sensitivity function document the importance of two other variables manipulated in this series of experiments: temporal change and retinal illuminance. Kelly (1971, 1979) reversed, over time, the light and dark bars of his gratings to measure the effect of temporal frequency on the contrast sensitivity function. His spatiotemporal contrast sensitivity function revealed that contrast sensitivity is best when temporal frequency is 1 Hz and spatial frequency is 4- 6 cpd of visual angle. From this peak, low spatial frequencies are generally aided by low temporal frequencies and high spatial frequencies are hurt by any change over time. In Experiment 2, motion was varied in order to test the effect of changes over time. Motion is an issue in the cockpit environment and can have different effects on CRT and LCD monitors. Van Nes and Bouman (1967) demonstrated that the contrast sensitivity function also depends on stimulus luminance. At high photopic levels, the peak contrast sensitivity is for 8 cpd stationary gratings. At scotopic levels, contrast sensitivity is best for 1 cpd gratings and declines with increased spatial frequency. Retinal illuminance was varied in Experiment 3 by using neutral density filters. Spectral filtering was varied in Experiment 4 in order to tease apart the effects of overall stimulus luminance and specific cone inputs.

In short, this series of experiments was designed to systematically examine contrast acuity for five types of tasks (Regan letter, bar grating, Tumbling E, Landolt C, and Landolt octagon) presented on three types of media (paper, CRT monitor, and LCD monitor) in order to provide guidance in designing a sensitive and reliable evaluation of the impact of LEP on aircrew vision. Candidate tests were further examined for generalization over well-established variables impacting contrast acuity: motion and retinal illuminance. Finally, the overall effect of retinal illuminance was dissociated from selective filtering in the visible band in order to both inform the evaluation of LEP and to better understand the relative importance of the three cones for contrast acuity.

Experiment 1

Rationale

Experiment 1 was designed to screen all five stimulus tasks presented on each of the three media in order to inform choices for Experiments 2- 4. In addition, the tests were conducted with people not requiring prescriptions to attain at least a Snellen Equivalent of 20 (emmetropes) for far stimuli and people who needed to wear either contact lenses or glasses (ametropes). Given the current effort to provide both LEP and prescriptions to aircrew, it was important to be certain that any test selected would be applicable to both groups.

Method

Participants

Sixteen emmetropes (10 males and 6 females) and 16 ametropes (3 males and 13 females) participated in Experiment 1. The groups were similar in age (means= 20.0 and 20.7, respectively; ranges= 18- 25 and 18- 29, respectively). They were recruited from PSY 1013 (Introduction to Psychology) in partial fulfillment of a course requirement.

Design

Each participant performed 34 trials in a single session lasting less than 1.5 hours. In a repeated-measures design, each participant viewed each of the five stimulus sets (Regan letters, bar gratings, Tumbling E stimuli, Landolt C stimuli, and Landolt octagons) at two contrasts (medium and low) on each of the three media (paper, LCD, and CRT). The Regan letters and bar grating tasks on paper were treated as hanging control tasks. They were performed at each of their two contrasts at the beginning of each of two blocks containing 18 and 16 trials. For all conditions, the medium contrast always immediately preceded the low contrast condition. After the four control trials, each of the five tasks (at each of the two contrasts) was performed on one of the monitors (3 on one type and 2 on the other). In the first block, the Tumbling E and either the Landolt C or the Landolt octagon tasks were performed on paper at each of their two contrasts. After the control trials in the second block, each task was run on the other monitor and the alternate Landolt task was run on paper. The order of the control tasks was counter-balanced across blocks for each participant and the order of tasks and monitors was counter-balanced across participants. It should be noted that the repetition of the control tasks (Regan letters and bar gratings on paper) permitted the computation of reliability estimates for those tasks.

Stimuli

Regan Letters

The same 8 letters used by Regan were used in these experiments: C, D, O, R, K, N, H, V, Z, and S. Bill Brockmeier had previously measured each Regan letter template in order to exactly reproduce his fonts in Graphite. The author is grateful to him for providing his measurements to permit the stimuli to be pixel-edited in PaintShop Pro for these experiments. While the Regan font has some virtues, the actual distribution of the confusability of letters across positions within rows and across rows was not well controlled in his charts. For these experiments, the confusable pairs (C & O, D & O, R & K, and N & H) were carefully controlled. Each row contained 8 letters: R, K, N, and H;

either C & O or D & O; and two of the three distinctive letters (V, Z, and S). The set of 8 letters chosen and the position of letters within a row were counterbalanced (given the constraint that highly confusable letters were not adjacent) across the 11 rows in each contrast stimulus on each media. As in the Regan charts, the stroke-width decreased from the top row to the bottom row. The binocular viewing distance was 11.5 feet in the lab. The smallest stroke-width (bottom row) contained 2 pixels and subtended .5 min of arc (Snellen Equivalent= 10). The top row (largest stroke width of 20 pixels) had a Snellen Equivalent of 100. Within pixels available, Snellen Equivalent approximately doubled every 3 lines. An example of a low contrast Regan letter chart is shown in Figure 1.1.

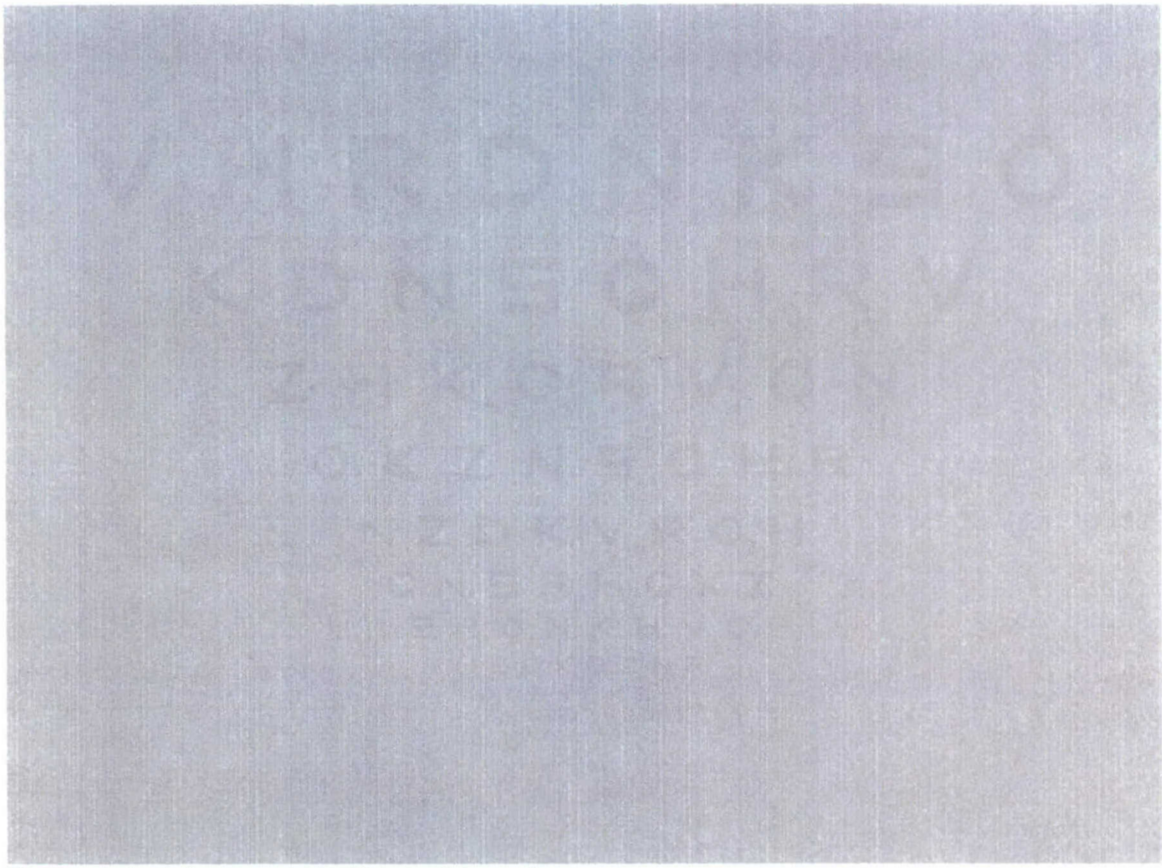


Figure 1.1 A low contrast Regan letter chart.

Bar Gratings

There were 8 rows of 8 stimuli on each chart. The left 4 stimuli on a row were one stroke-width and the right 4 stimuli were next sized stroke-width. The smallest pair of stroke-widths was at the top of each chart and the largest pair of stroke-widths was at the bottom of the chart. Size within a row was alternated across rows and counter-balanced across the two contrasts and across the three media. The four orientations (vertical, upper right, horizontal, and upper left) occurred once within each size and the orders were counter-balanced. Having 2 sizes for each of the 8 rows permitted 16 sizes

that varied between a Snellen Equivalent of 10 and 100 (number of pixels per stroke-width were 2-14, 16, 18, and 20). Each stimulus had a constant diameter (95 pixels or 23.7 min of arc), so the number of cycles per circular window decreased with increased stroke-width. Figure 1.2 shows an example of a low contrast bar grating chart.

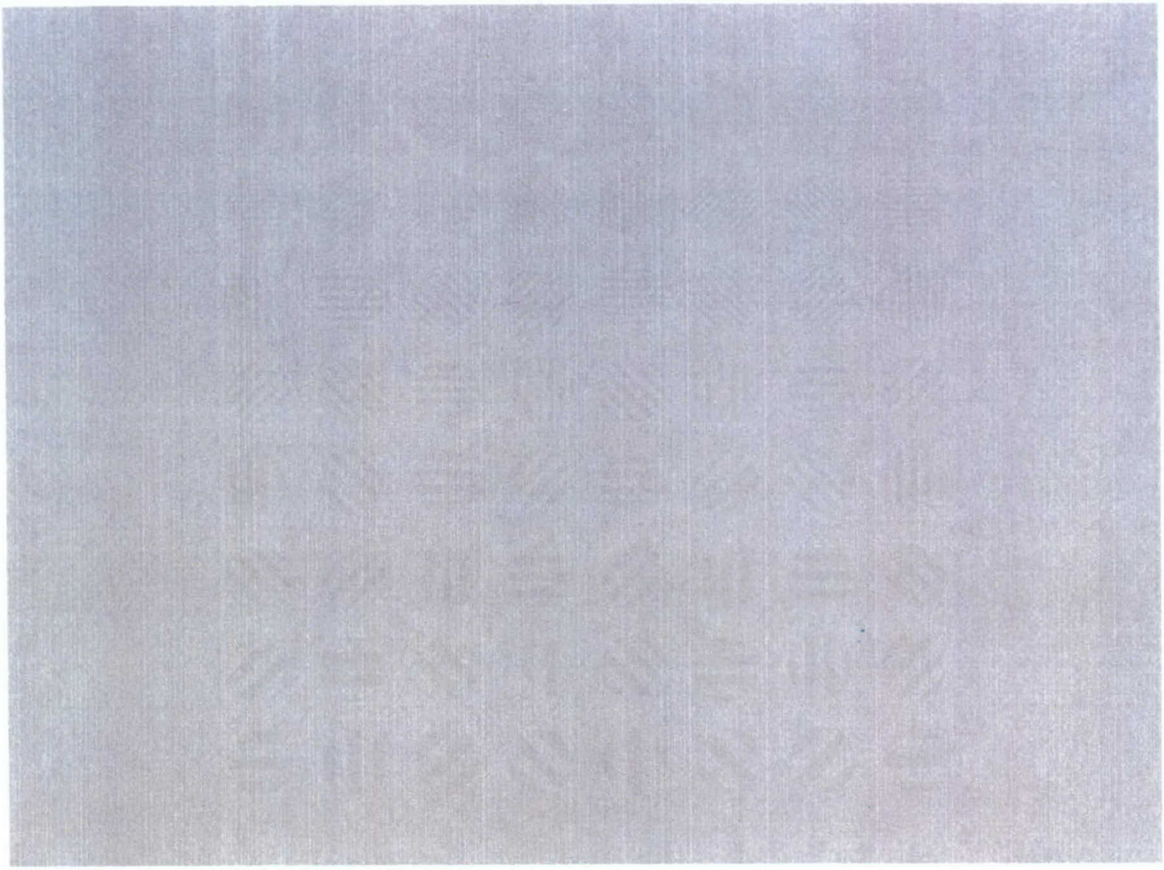


Figure 1.2 A bar grating chart.

Tumbling E Stimuli

Each Tumbling E is a square (5 stroke-widths X 5 stroke-widths) without any serif. There were four orientations (up, right, down, and left) and the same 16 stroke-widths as with the bar gratings. As with the bar gratings, each orientation occurred once in each set of four stimuli within a size. As with the letters, but unlike the gratings; stimulus size increased with stroke-width. See Figure 1.3

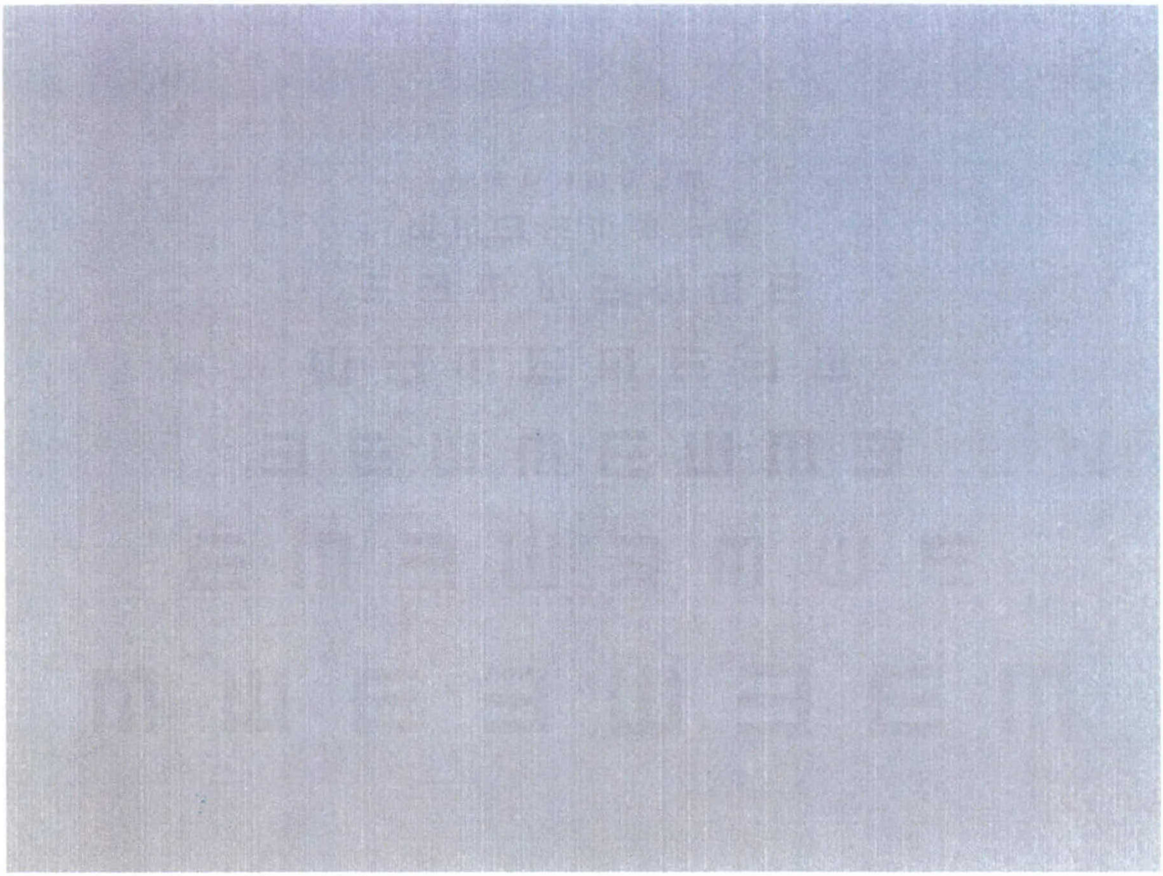


Figure 1.3 A Tumbling E chart.

Landolt C Stimuli

The same 16 stroke-widths (Snellen Equivalents) were used in a similar array of 8 rows of 2 sizes of 4 stimuli. On the other hand, there were 8 orientations of the square gap: 4 cardinal directions (top, right, bottom, and left)and 4 diagonals (upper right, lower right, lower left, and upper left). Two cardinal orientations and two diagonals were chosen for each set of 4 stimuli of the same size. The other orientations were used for the set of 4 stimuli of the next size on the same row. See Figure 1.4.

Landolt Octagons

The Landolt octagons are the same as the circles, except the gap is placed in a pixel- aligned octagon (two horizontal, two vertical, and four diagonal sides). As previously noted, the 2-pixel "circles" for the Cs were really octagons. See Figure 1.5.

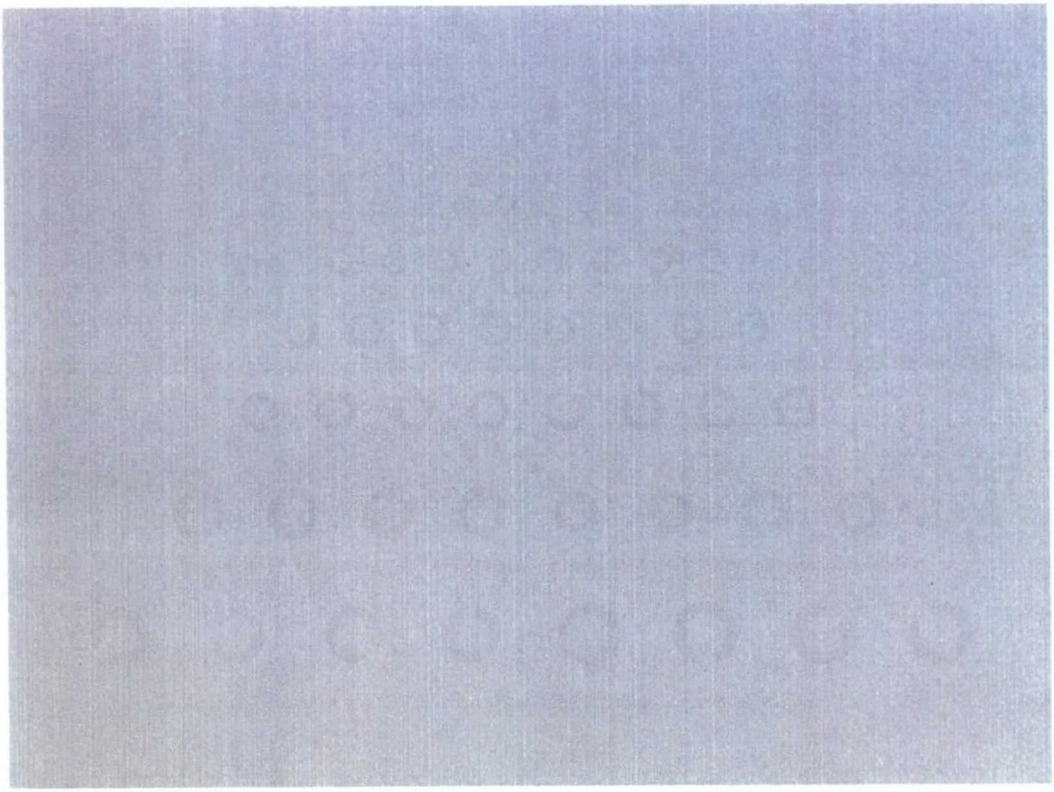


Figure 1.4 Landolt C chart.

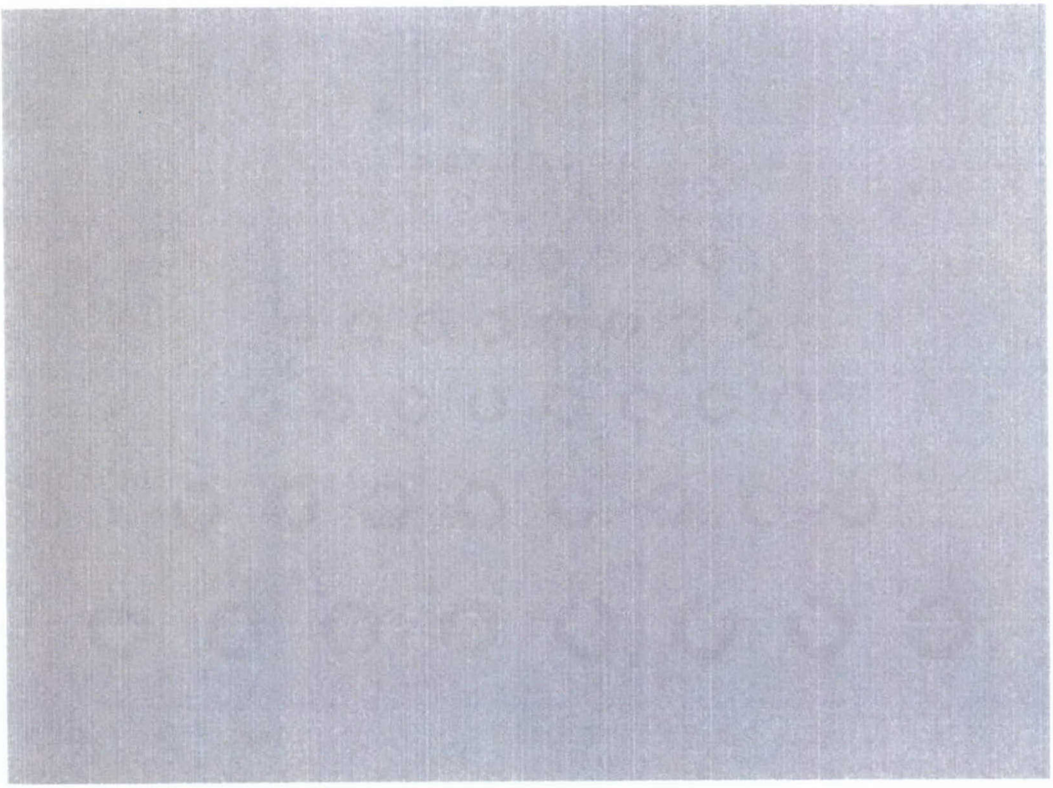


Figure 1.5 Landolt octagon chart.

Apparatus.

All stimuli were binocularly viewed while seated at a distance of 11.5 feet (the maximum available given CRT depth) in a fluorescently lit lab. The printed paper stimuli were mounted on foam board and presented on a small easel on a table slightly below eyelevel and about the same height as the middle of the Dell 20" LCD and the Hitachi SuperScan Supreme 21" CRT. The native resolution for the LCD (1600 X 1200) was used for both monitors. Both display sizes were adjusted to 16" X 12" and all stimuli were presented at 100 dpi. The brightest setting for the CRT limited the background used for the three media: mean of 116 cd/m^2. As metered by a Minolta CS100A, an RGB of 255 produced 114.6 cd/m^2 for the CRT, an RGB of 193 produced 115.6 cd/m^2 for the LCD, and the light reflected off of a pastel grey paper produced 117.4 cd/m^2 for the paper stimuli. The CS100A was also used to calibrate the RGB values for the stimuli. The medium contrast stimuli had a Weber contrast of .500 (minimum of .498 for the CRT and maximum of .503 for the LCD); while the low contrast stimuli had a Weber contrast of .114 (minimum of .113 for the paper and CRT and maximum of .116 for the LCD).

Procedures.

The ametropes wore untinted prescription contacts or spectacles. Participants were free to take breaks as needed and were required to take a break between blocks.

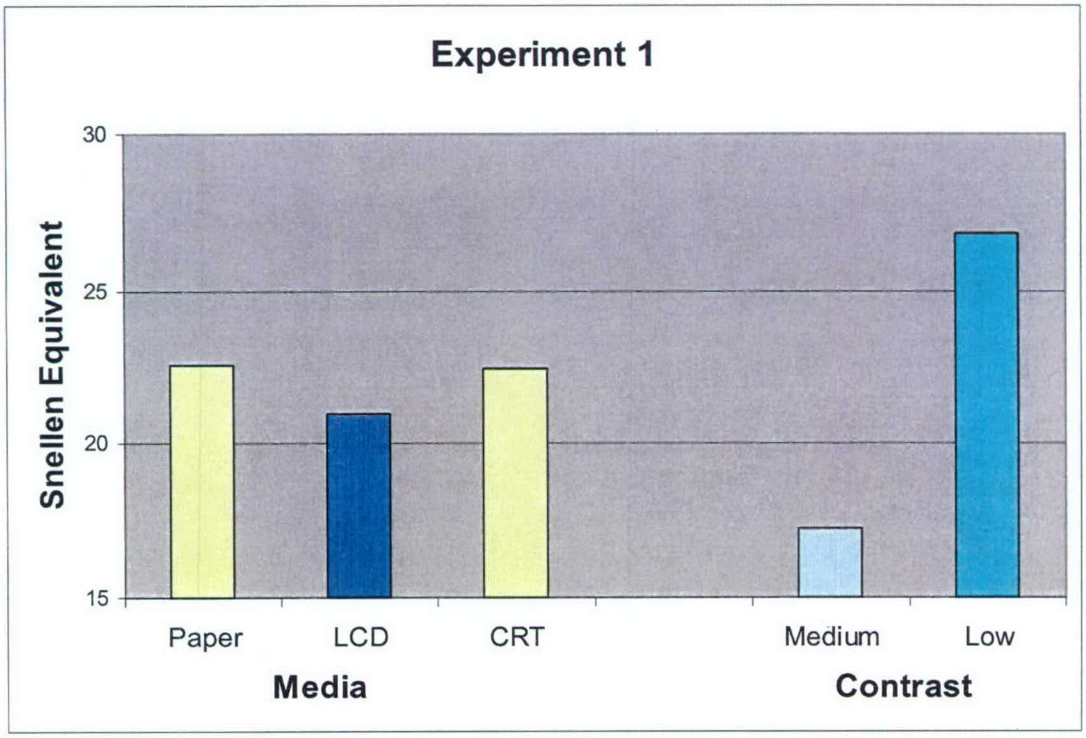
For a given chart, the participant started with the smallest sized stimulus that they could accurately report and continued to smaller stimuli until less than 2 stimuli could be correctly reported of a given size. If an error was made on the original size, the participant was instructed to move up a size and begin again. Responses were recorded on paper data sheets and were later manually entered and checked into a spreadsheet that computed Snellen Equivalents.

A number of participants had difficulty reporting "horizontal" and "vertical" and distinguishing between left and right. All orientations with the correct response were presented on a blackboard to the left of the participant and the participants were encouraged to use it whenever necessary. Especially left vs. right and the diagonals still posed problems for some participants. The use of hand signals was allowed in order to improve the reliability of their responses.

Results

The Snellen Equivalents were analyzed by a 2 (the emmetrope vs. ametrope organismic variable) X 5 (tasks: Regan letter, bar grating, Tumbling E, Landolt C, and Landolt octagon) X 2 (medium and low contrast) X 3 (media: paper, LCD, and CRT) mixed ANOVA. Greenhouse-Geisser epsilon-adjusted degrees of freedom were computed to protect against violations of sphericity. The slight mean advantage for the uncorrected emmetropes relative to the corrected vision ametropes was not significant; $F(1, 30) = 1.422$; $p = .242$. It also did not enter into any significant interactions. There was a significant difference between media {$F(1.945, 58.346) = 38.372$; $p < .001$}, acuity was better (smaller Snellen Equivalent) for the medium contrast stimuli than for the low contrast stimuli tasks {$F(1, 30) = 248.987$; $p < .001$}, and there was a significant media X contrast interaction {$F(1.651, 49.545) = 25.674$; $p < .001$}. These main effects and the interaction are shown in Figure 1.6. Orthogonal comparisons revealed that acuity was

better for the LCD than for the paper and CRT media {F(1, 30)= 73.822; p< .001}, but the effect is much larger for the low contrast stimuli {F(1, 30)= 35.192; p< .001}. There was also a slight advantage of the CRT over paper low-contrast stimuli {F(1, 30)= 15.420; p< .001}.



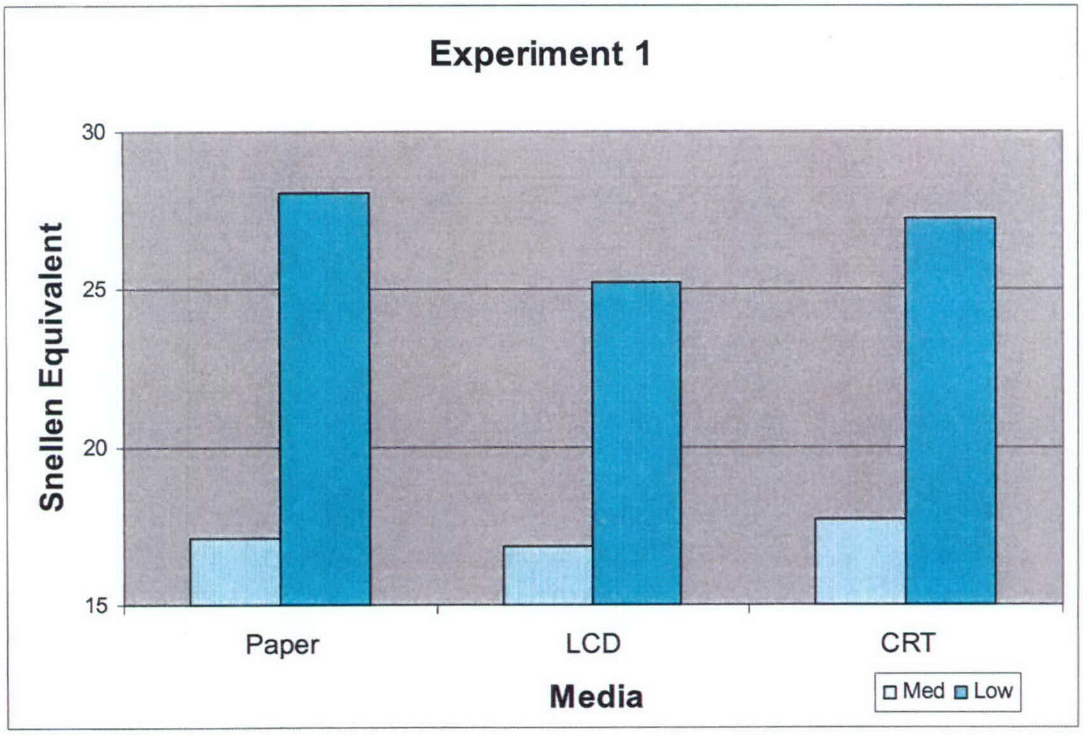


Figure 1.6 Effects of media, contrast, and interaction.

As can be seen in Figure 1.7, there was also a main effect of task {F(3.186, 95.582)= 33.966; p< .001} and a task X contrast interaction {F(3.362, 100.867)= 23.487; p< .001}. Bonferroni-adjusted multiple pairwise comparisons revealed that acuity was better for Tumbling E stimuli than for Regan letters (p= .044), that Regan letters did not differ from bar gratings (p= 1.000), that Landolt octagons did not differ from Landolt C stimuli (p= .266), and that the Landolt stimuli were worse than Regan letters and bar gratings (ps <= .001). While the task X media interaction was not significant {F(5.245, 157.361)= 1.755; p= .122}, there was a hint that the Landolt octagons might be more sensitive to LCD and CRT differences than the Landolt C stimuli.

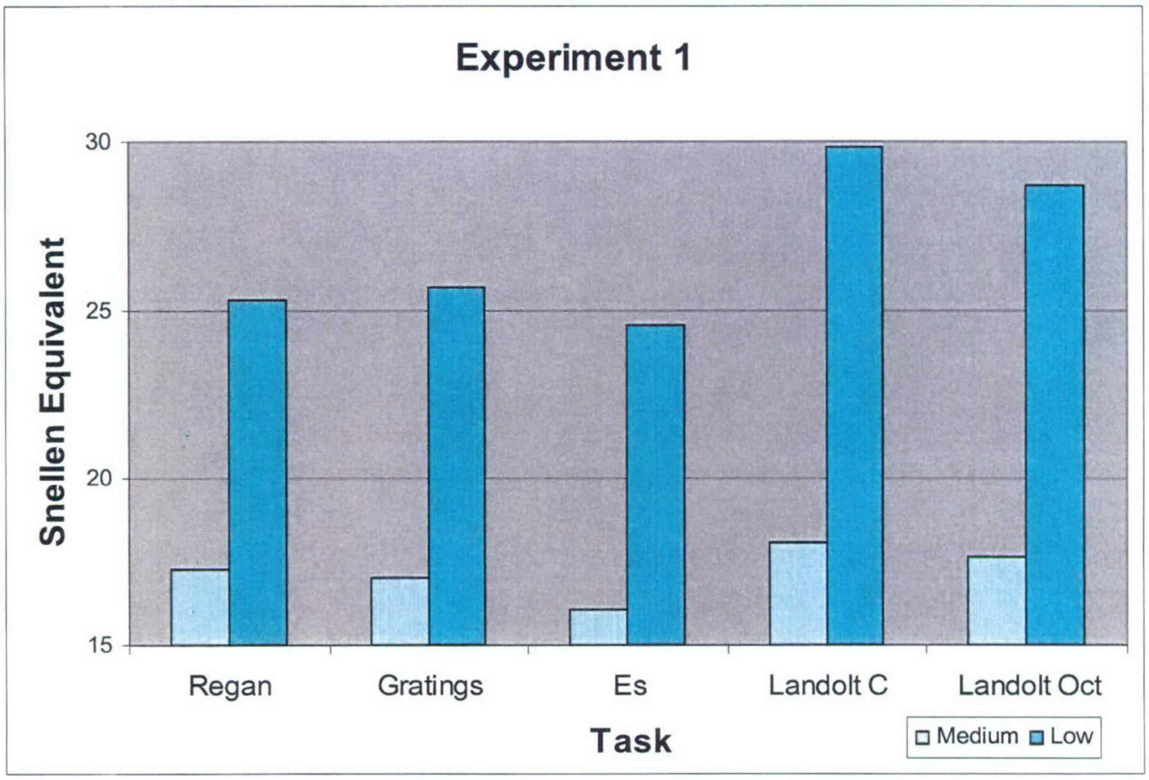


Figure 1.7. Main effect of task and the task X contrast interaction in Experiment 1

Correlations of Snellen Equivalents between conditions and across participants were calculated to gain insights about the reliability and construct validity of the five tasks. As will be recalled, each participant repeated the Regan letters and bar grating tasks on paper. This permitted a direct measure of test-retest reliability. Reliability was good for both tasks, but was higher for the low contrast stimuli (r= .922 and .943 for the Regan letters and bar gratings) than for the medium contrast stimuli (r= .842 and .786). Restricted range may have been a problem for the medium contrast stimuli.

In order to estimate construct validity, correlations were computed for the same task and contrast across different media and for the same task and media across the two contrasts. The means of those correlations are shown in Table 1.1. As with the reliability measures, correlations were generally higher for the low contrast stimuli than for the medium contrast stimuli. As for tasks, the Regan letter and bar grating tasks were more

consistent than the Tumbling E and Landolt C tasks. The surprising result is that the Landolt octagons were comparable to the Regan letters and the bar gratings.

Table 1.1 Correlations for the five tasks of Experiment 1 across media and contrasts.

Same Task and Contrast, Different Media					
Contrast	Letters	Gratings	Es	Landolt Cs	Octagons
Medium	0.861	0.779	0.783	0.694	0.741
Low	0.851	0.875	0.722	0.775	0.847

Same Task and Media, Different Contrasts				
Letters	Gratings	Es	Landolt Cs	Octagons
0.732	0.768	0.672	0.670	0.748

Conclusions

Clearly any evaluation of acuity with LEP should include low contrast stimuli. The use of low contrast stimuli provides more sensitive measures of differences between tasks and between media. It also generally produced higher reliability and construct validity estimates than medium contrast stimuli.

The Regan letter and bar grating tasks appear to be better tasks than the Tumbling E and the Landolt C tasks for screening purposes. The Tumbling E was the easiest task and that may have led to the relatively low correlations with the low contrast stimuli. While Landolt C stimuli are excellent stimuli with trained observers, the PSY 1013 students had trouble with some directions. This undoubtedly lowered the bar grating correlations some, but the inclusion of an additional 4 orientations with the Landolt C stimuli seemed to exacerbate the problem. The pleasant surprise was the correlations for the Landolt octagons. They also hinted at detecting a difference between the LCD and CRT monitors. Regan letters, bar gratings, and Landolt octagons were selected for further use in Experiment 2.

The advantage of the LCD monitor over the paper and CRT stimuli was substantial. One possible reason is the fixed pixels in an LCD in its native resolution compared to the possible misalignment of the RGB guns in a CRT. It is also possible that this advantage may be limited to static images. This possible limit to generalizability was tested in Experiment 2.

Experiment 2

Rationale

Experiment 2 was designed to investigate the effect of motion on the three most promising stimulus tasks: Regan letters, bar gratings, and Landolt octagons. The jittery motion of a cockpit can make the displays more difficult to read, so any contrast acuity task for evaluating LEP should be generalizable across static and moving displays. LCD displays might be less suitable for testing operationally relevant moving displays, since LCD monitors can produce ghost traces due to lower refresh rates and shuttering relative to CRT monitors (PC World, 2003; Wright, 2002). Since it was anticipated that contrast acuity would be reduced for moving stimuli, a high contrast condition was added to the medium and low contrasts used in Experiment 1. Being unable to create dynamic paper displays, only the LCD and CRT media were tested.

Method

Participants

There were 48 participants in Experiment 2: 19 males and 29 females. Their mean age was 18.5 years (range= 17- 30 years). They were recruited from PSY 1013 (Introduction to Psychology) in partial fulfillment of a course requirement. A 49th participant was replaced due to poor acuity (greater than Snellen Equivalent 20 with the Regan letters). This may have been in part due to a first-language bias (top-down process) rather than due a sensory (bottom-up process). The subject almost always reported the letter "O" as a "Q".

Design

Participants were randomly assigned to two groups of 24. All participants tested the Regan letters and a second stimulus type. In addition to Regan letters, one group tested the bar gratings, while the other group tested the Landolt octagons. For each stimulus type, each participant tested the stimulus at three contrasts (high, medium, and low) at each of three speeds (stationary, slow, and fast) on each of two media (LCD or CRT). The 36 conditions were tested in a single session about 1.5 hours long. There were 12 blocks of 3 trials: a stimulus type on one medium in the high, medium, and low contrast conditions in that order. The combinations of the three speeds to the three contrasts were determined by a graeo-latin square such that within 4 blocks of three trials, each stimulus type was tested on each monitor and the three speeds were tested four times. There were three of these sets of four blocks of three trials. The orders within sets and the orders of sets were counter-balanced across participants.

Stimuli.

The medium and low contrast Regan letters and bar gratings on LCD and CRT media stimuli from Experiment 1 were used again in Experiment 2. New counter-balanced orders of Regan letters and bar gratings were created and implemented in PaintShop Pro to create high contrast (Weber 91.6% contrast) stimulus charts. The LCD and CRT RGB values were set to 50 and 10 to generate 91.6% and 91.5% contrasts, respectively. All of the PaintShop Pro format files were exported to bitmap files (BMP) each of which was 1.28M in size.

Apparatus.

The same LCD and CRT from Experiment 1 were used in Experiment 2, but both displays were driven by the same PC: a Dell owned by the PI with a NVIDIA GeForce4 Ti 4600 with DVI (for the LCD) and analog (for the CRT) outputs. In order to create "motion", a given BMP stimulus file was translated by a predetermined sequence of offsets using Neurobehavioral Systems Presentation. The NVIDIA graphics was able to reliably maintain a 20 Hz frame rate of the 1.28M images without dropping a frame. Since the same graphics card was used to present the stimuli to the LCD and CRT monitors, any psychophysical difference could confidently be attributed to the monitor rather than the graphics card presentation. As in Experiment 1, both monitors were set at a 60 Hz refresh rate (the maximum for the resolution on the LCD). The sequence of offsets was based on an 11 x 11 matrix of 3 pixels. All offsets that were common to any bar grating vertical, horizontal, or diagonal overlap were eliminated in order to avoid spatial aliasing. The resulting 81 valid offsets were sampled without replacement in an erratic, clockwise sequence. This sequence was looped in the Neurobehavioral Systems Presentation to produce a jittery motion of the whole display for as long as the participant needed to respond. No loop was run for the stationary condition. The loop was run at 12 Hz (1/5 the refresh rate) for the slow motion condition and at 20 Hz (1/3 the refresh rate and maximum through put) for the fast motion condition. While erratic, the average velocity was 1.88 deg/sec for slow motion (range= 0.30- 3.84 deg/sec) and was 3.14 deg/sec for fast motion (range= 0.50- 6.40).

Procedures.

The procedures for Experiment 2 were the same as for Experiment 1, except that participants were actively encouraged to take some time getting used to the moving displays for the first few blocks. Initially, some observers lacked confidence that they could see anything the first time they saw a low contrast, fast moving display. Practice and confidence helped.

Results

Snellen Equivalents were analyzed in a 2 (Groups: other task was bar gratings or Landolt octagons) X 2 (Task: Regan letters or other) X 3 (Contrast: High, Medium, or Low) X 2 (LCD or CRT) X 3 (Motion: none, slow, or fast) mixed ANOVA. There was no main effect of group ($F < 1$), but it entered into a number of interactions due to the "other task" (bar gratings or Landolt octagons). Consistent with Experiment 1, acuity decreased as contrast was reduced {$F(1.085, 49.913)= 608.564$; $p< .001$}, acuity was better for the LCD than for the CRT {$F(1, 46)= 184.132$; $p< .001$}, and the LCD advantage increased with reduced contrast {$F(1.771, 81.474)= 8.862$; $p= .001$}. These results must be interpreted in terms of the main effect of tasks and higher order interactions. In general, Regan letter acuity was better than "other task" acuity {$F(1, 46)= 23.728$; $p< .001$}; but the magnitude depended upon the other task {$F(1, 46)= 5.868$; $p= .019$}. Bar grating acuity was only slightly worse than Regan letter acuity, but acuity for Landolt octagons was much worse than for Regan letters. Not surprisingly, the Regan letter advantage increased with reduced contrast {$F(1.418, 65.235)= 42.708$; $p< .001$}, as did the interaction with other task {$F(1.418, 65.235)= 9.829$; $p= .001$}. The Regan letter advantage was larger for the CRT than for the LCD {$F(1, 46)= 8.660$; $p= .005$} and this

interaction increased with reduced contrast {$F(1.515, 69.686)= 4.787$; $p= .019$}. These results are shown in Figure 2.1. The LCD advantage was mainly due to low contrast, bar gratings and Landolt octagons. Also note that acuity was a linear function of reciprocal contrast.

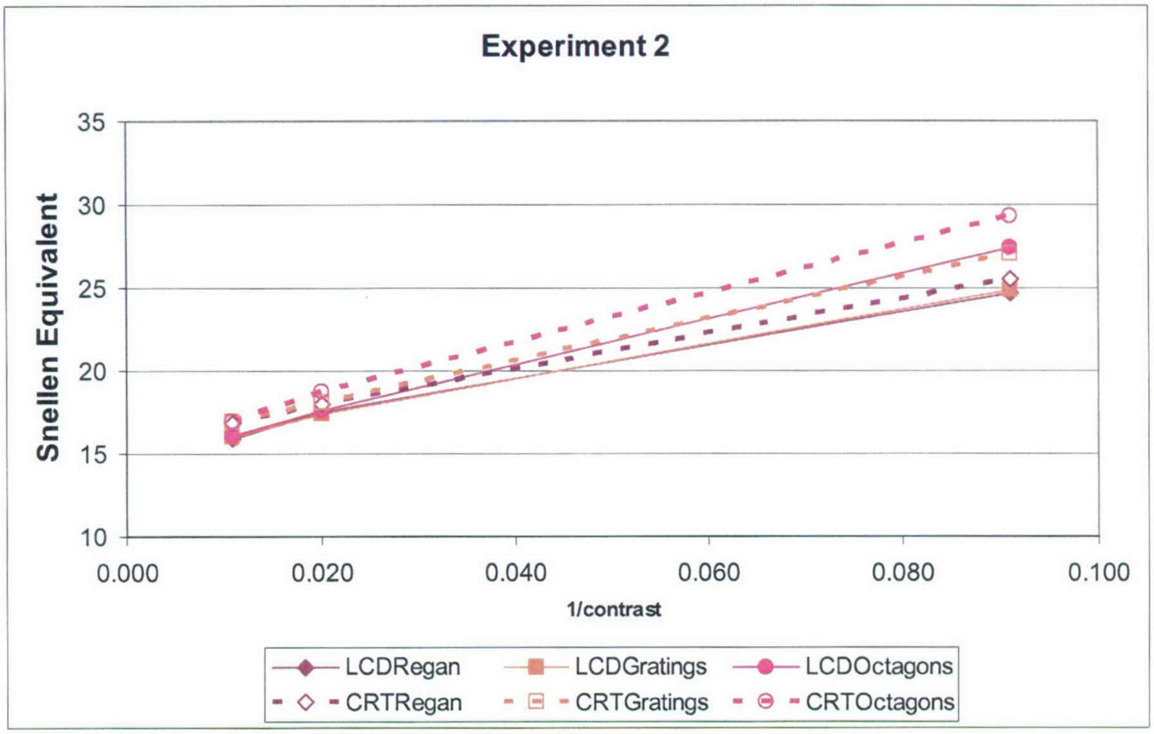


Figure 2.1 Effects of contrast, monitor, and tasks in Experiment 2.

The effect of motion was a major focus of Experiment 2. Acuity decreased with speed; $F(1.908, 87.773)= 254.213$; $p< .001$. Orthogonal comparisons revealed that stationary acuity was superior to moving acuity {$F(1, 46)= 405.881$; $p< .001$} and that fast motion was worse than slow motion {$F(1, 46)= 35.515$; $p< .001$}. The effect of motion increased with reduced contrast; $F(3.472, 159.72)= 2.753$; $p= .037$}. It was hypothesized that motion might have a bigger impact with the LCD monitor than with the CRT monitor. The only hint of such an effect was the motion X contrast X monitor interaction and it only approached significance; $F(2.615, 120.270)= 2.371$; $p= .082$. That interaction is shown in Figure 2.2. As can be seen, the acuity with the LCD monitor is always better than with the CRT, but that difference decreases as speed increases. Stated the other way, increasing the speed from slow to fast hurt LCD acuity more than it hurt CRT acuity.

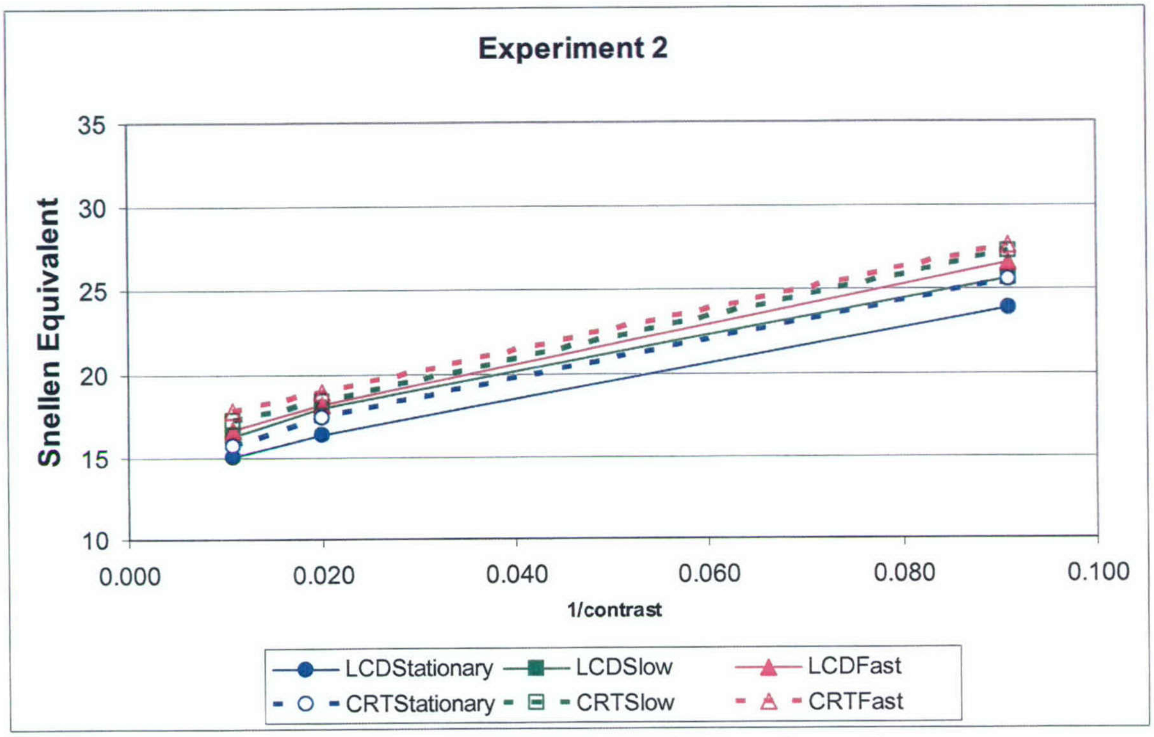


Figure 2.2 Effects of contrast, monitor, and motion in Experiment 2.

The effect of motion also depended on the task (Regan or "other task"); $F(2.000, 91.991) = 22.850$; $p < .001$. The effect of motion also was larger for the Landolt octagons than for the Regan letters and the bar gratings; $F(2.000, 91.991) = 10.040$; $p < .001$. These results are shown in Figure 2.3. It should be noted that separate ANOVAs were run for each task. All of the main effects were significant for each task (Regan letters, bar gratings, and Landolt octagons), but the only significant interactions were with the Regan letters and bar gratings.

Conclusions

The major effects of Experiment 1 were replicated in Experiment 2. Including motion in Experiment 2 produced reliable results and logical interactions with contrast and tasks. On the other hand, the magnitude of the effect was smaller than for monitor: LCD acuity was always better than CRT acuity. Obviously the effect of motion would increase and perhaps might even over ride the effect of monitor if the frame rate were increased by using a smaller stimulus or a faster graphics card.

In terms of evaluating LEP, erratic motion does not seem to be critical; although the effect would be expected to increase with haze and multiple reflections of an LEP. When it is deemed important to evaluate motion with the LEP, these data indicate that an LCD monitor is at least as effective as a CRT monitor. As for tasks, the Regan letters and bar gratings provided more reliable results than the Landolt octagons. Regan letters and bar gratings were chosen for inclusion in Experiments 3 and 4.

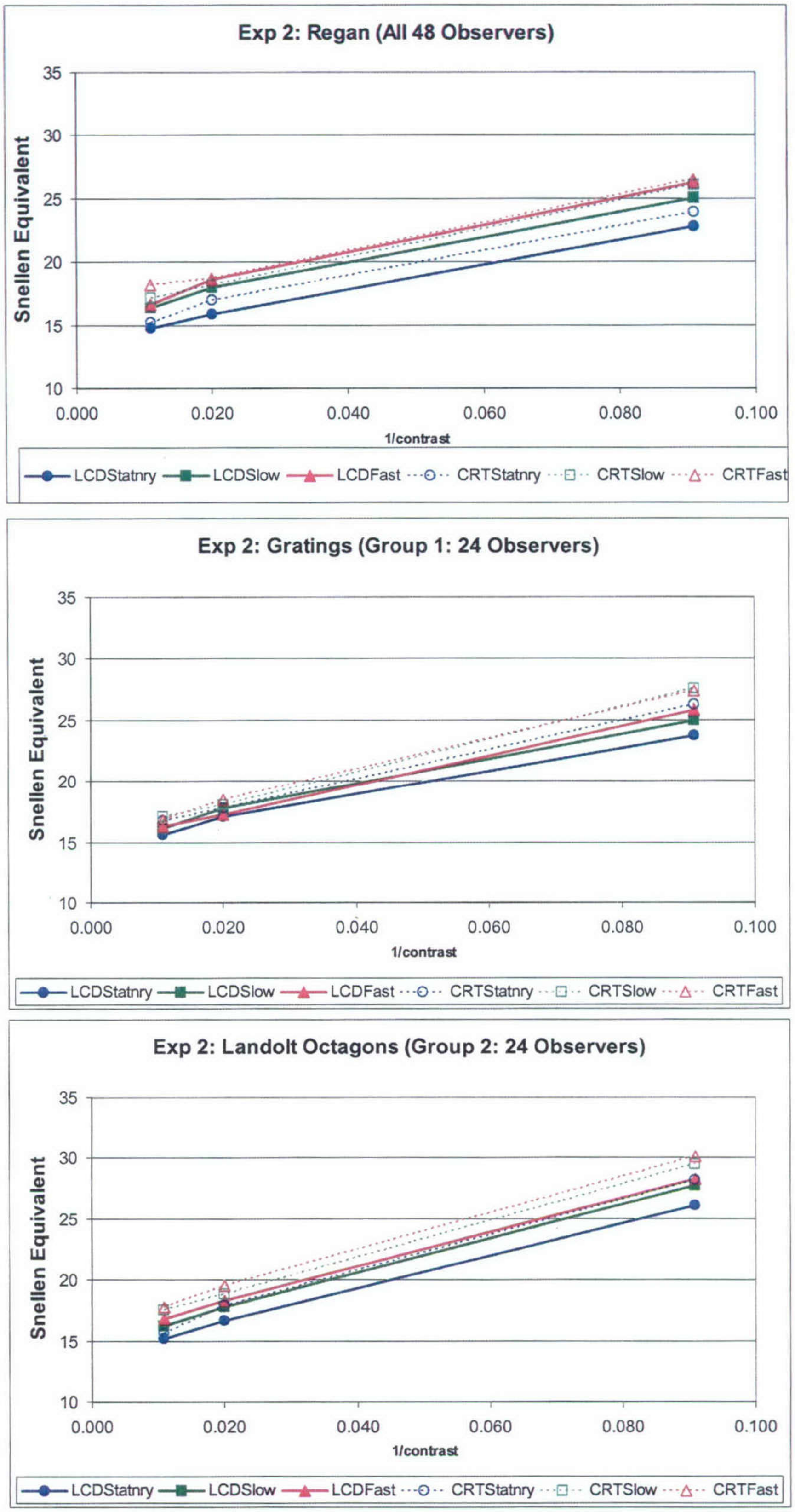


Figure 2.3 Effects of contrast, monitor, and speed for each task in Experiment 2.

Experiment 3

Rationale

The goal of Experiment 3 was to investigate the impact of reduced retinal illuminance on contrast acuity for the two best stimulus tasks: Regan letters and bar gratings. The purchase of new LCD and CRT monitors and the colorimetric matching of the stimuli permitted the testing of potential differences between the paper, LCD, and CRT media.

Method

Participants.

Eighteen participants (3 males and 15 females) were recruited from PSY 1013 (Introduction to Psychology) and completed all six sessions for 2 hours credit toward the fulfillment of the course requirement and for $60 compensation. Their mean age was 19.7 years (range= 17- 25). The 17 year-old provided written parental consent. At the completion of the first session, each participant was asked if they wished to participate in the additional five sessions. While they could not receive any more credit toward the course requirement, they were paid $10 for each additional session and an extra $10 as a completion bonus. Subsequent sessions were scheduled at the mutual convenience of the participant and one of the three research assistants. Two additional students discontinued after 3 additional sessions each and two students only wanted to earn PSY 1013 credit and declined to participate for pay.

Design.

Experiment 3 was a 2 stimulus tasks (Regan letters and bar gratings) X 3 contrast (high, medium, and low) X 3 media (paper, LCD, and CRT) X 10 retinal illuminants (provided by the 10 neutral density (ND) filters described below) repeated measures design. Each of the six sessions lasted just over an hour and was comprised of 10 blocks of 3 trials. The photopic luminance transmittance (PLT) of the 10 ND filters were very close to their designed nominal values: clear, 80%, 60%, 50%, 40%, 30%, 20%, 10%, 5%, and 1%. The 10 filters were split into two interleaved sets of five filters: clear, 60%, 40%, 20%, & 5% and 80%, 50%, 30%, 10%, and 1%. Each of the two filter sets was tested on three separate sessions of the six sessions. Two of the blocks of three trials in a session were performed with each of the relevant session's ND filters. These two blocks were consecutive in order to minimize adaptation time (at least 3 minutes) between filter changes. One block was with the Regan letters on one media and the other block was with the bar gratings on a different media. As in Experiment 2, the order of trials was always high, medium, and low contrast. The specific combinations of ND filter and media were determined by a graeco-latin square. The order of blocks within a session and combinations across sessions were counter-balanced with the constraint that each of the three media were tested at least 3 times across the 10 blocks is each session.

Stimuli.

The orders for the stimuli in each row for the Regan letters and bar grating charts on LCD and CRT media were the same as those used in Experiment 2. The orders for the medium and low contrast paper in Experiment 1 were used in Experiment 2. New orders for the high contrast stimuli were generated. In order to equate both luminance and color

across the media, all new physical stimuli were generated in PaintShop Pro and printed on new paper and displayed on the new LCD and CRT monitors.

Apparatus.

New PCs and monitors were purchased with the grant so that no psychophysical difference could be due to age or alignment of the equipment. The CRT was a Sony GDM-C520K 21" CRT. It is specifically designed for professional color displays. It includes a sensor and software to calibrate the color temperature of the display. It also includes a hood to reduce the impact of overhead ambient room illumination. The LCD was a Sony SDM-X202 20" LCD monitor. It has a 1600 X 1200 native resolution, so screen resolution, horizontal and vertical adjustment, and refresh rates for the monitors were equated to each other as in Experiments 1 and 2. To be similar to the CRT, a hood was constructed out of matte black foam board for the LCD monitor.

A Minolta CS100A was used to calibrate the monitors and to match the brightness and color of the three media. PowerPoint was used to generate circle calibration stimuli. The stimulus to be metered was surrounded by a black annulus to assure alignment with the CS100A. The new RGB values, brightnesses (in cd/m2), color (x and y), and Weber contrasts are given in Table 3.1. It should be noted that the temperature of the CRT was also adjusted to aid in matching the color values.

Table 3.1. Stimulus values chosen for Experiment 3.

Paper	R	G	B		Y	x	y	Weber %
"White"	255	255	255		121	0.387	0.399	
Low	235	235	235		104	0.385	0.398	14.05
Med	166	166	166		58.3	0.380	0.394	51.82
High	24	24	24		10.4	0.397	0.400	91.40

LCD	R	G	B		Y	x	y	Weber %
"White"	227	195	110		122	0.391	0.399	
Low	210	183	103		105	0.385	0.401	13.93
Med	156	132	83		58.2	0.380	0.396	52.30
High	60	53	30		10.3	0.397	0.398	91.56

CRT	R	G	B		Y	x	y	Weber %
"White"	234	228	238		122	0.387	0.398	
Low	215	213	225		105	0.383	0.398	13.93
Med	154	154	180		58.6	0.380	0.395	51.97
High	32	24	70		10.2	0.399	0.400	91.64

The 10 ND spectacles were manufactured by United States Air Force's School of Aerospace Medicine (USAF / SAM) for the Optical Radiation Branch of the Air Force Research Laboratory's Human Effectiveness Directorate (AFRL / HEDO) to provide baselines to compare to LEP (Martinsen, 2005). USAF / SAM manufactured two pairs of spectacles at each of 10 nominal ND photopic luminance transmittances (PLTs). Each lens of all 20 ND spectacles was measured at AFRL / HEDO by Bill Brockmeier, Lucas

Chavey, and Gary Martinsen with some slight assistance from the PI. The ND spectacles were scanned from 200- 1400 nm with a Cary5. A HazeGard+ was used to measure transmittance, haze, and clarity. A Humphrey LensAnalyzer (LA360) was also used to measure the PLT and transmittance spectra of the ND spectacles. The optical quality of the spectacles was excellent: maximum haze for a lens= 1.89% and minimum clarity for lens= 97.7%. The PI was permitted to use the better pair of spectacles at each ND (lower haze, higher clarity, or better match across the lenses) for Experiment 3. The high optical quality, close matching across lenses, and close match to nominal PLT of these ND spectacles are shown in Table 3.2. Figure 3.1 shows that transmittance was very flat across the region of the visible spectrum with highest cone sensitivities.

	Nominal	Carey5					Hazegard+			LA360
	PLT	PLT	x	y	z	SLT	%Trans.	Haze	Clarity	Visible%
ND01BL	1%	0.894	0.345	0.330	0.324	0.823	0.95	0.19	100.0	1
ND01BR		0.688	0.353	0.327	0.320	0.624	0.74	0.26	100.0	1
ND05BL2	5%	4.659	0.326	0.331	0.343	4.425	4.90	0.11	100.0	5
ND05BR2		4.633	0.334	0.333	0.333	4.235	4.84	0.11	100.0	5
ND10BL	10%	9.648	0.324	0.330	0.347	9.187	10.00	0.49	97.7	10
ND10BR		9.280	0.327	0.332	0.340	8.676	9.70	0.29	99.8	10
ND20BL	20%	18.527	0.340	0.338	0.322	16.114	19.40	0.08	99.8	19
ND20BR		18.644	0.335	0.336	0.329	16.601	19.20	0.15	99.8	19
ND30BL	30%	27.082	0.332	0.334	0.334	24.392	28.10	0.12	99.8	30
ND30BR		27.622	0.335	0.335	0.331	24.599	29.00	0.09	99.8	29
ND40AL	40%	37.706	0.320	0.326	0.354	36.074	39.10	0.94	99.6	39
ND40AR		38.605	0.322	0.327	0.351	36.621	40.60	0.43	99.6	40
ND50BL	50%	48.533	0.324	0.328	0.349	45.570	50.70	0.11	99.8	49
ND50BR		48.788	0.323	0.327	0.350	46.010	50.50	0.11	99.8	50
ND60BL	60%	57.456	0.321	0.325	0.354	54.564	60.20	0.22	99.8	59
ND60BR		58.268	0.321	0.325	0.354	55.346	60.60	0.25	99.8	61
ND80BL	80%	76.859	0.315	0.320	0.364	75.132	80.00	0.14	99.8	81
ND80BR		76.339	0.316	0.321	0.364	74.458	79.90	0.18	99.8	80
NDCLBL	Clear	91.831	0.311	0.317	0.372	91.655	96.60	0.17	99.8	97
NDCLBR		92.426	0.311	0.317	0.372	92.191	96.80	0.20	99.7	97

Table 3.2 Optical characteristics of the 10 ND spectacles (20 lenses) of Experiment 3.

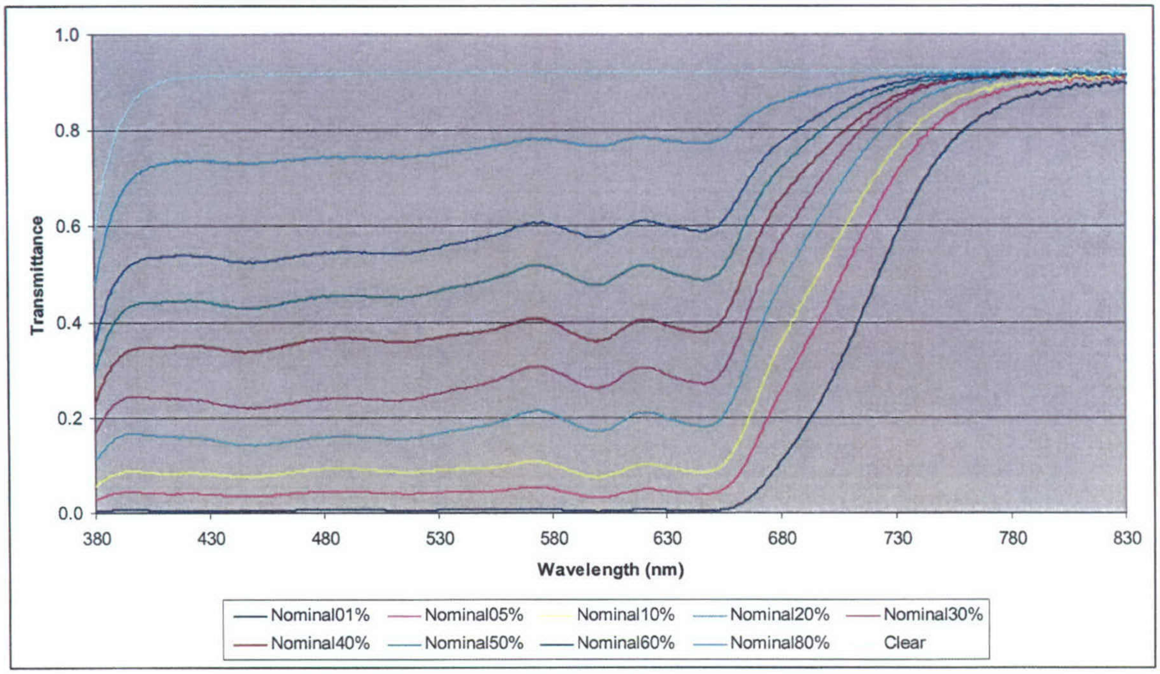


Figure 3.1 Transmittance spectra of the 10 ND spectacles of Experiment 3.

Procedures.

The procedures were the same as in Experiment 1, except that the observer was required to adapt to each ND spectacle for at least 3 minutes before beginning to report the stimuli. Adaptation was repeated if the spectacle was removed during a break. It should also be noted that many participants cupped their hands around the sides of the ND spectacles (especially the low transmittance ND spectacles) in order to minimize ambient and back-reflected light.

Results

The Snellen Equivalents were analyzed in a 2 (task: Regan letters and bar gratings) X 3 (contrast: high, medium, and low) X 10 (ND filters) X 3 (media: LCD, CRT, and paper) repeated measures ANOVA. Consistent with the results of Experiment 2, Regan letter acuity was better than for bar gratings {$F(1, 17)= 47.377$; $p < .001$}, reduced contrast hurt acuity {$F(1.015, 17.261)= 290.464$; $p< .001$}, and the Regan letter advantage increased as contrast was reduced {$F(1.128, 19.170)= 8.383$; $p= .008$}. Experiment 3 included the 10 ND spectacles. Reduced ND transmittance hurt acuity; $F(1.268, 21.562)= 231.204$; $p< .001$. The main effect of ND transmittance was larger for the bar gratings than for the Regan letter {$F(2.598, 44.173)= 6.862$; $p= .001$} and increased as contrast was reduced {$F(1.660, 28.212)= 188.317$; $p< .001$}. The Task X Contrast X ND transmittance interaction was also significant {$F(3.344, 56.850)= 5.706$; $p= .001$}and is shown in Figure 3.2.

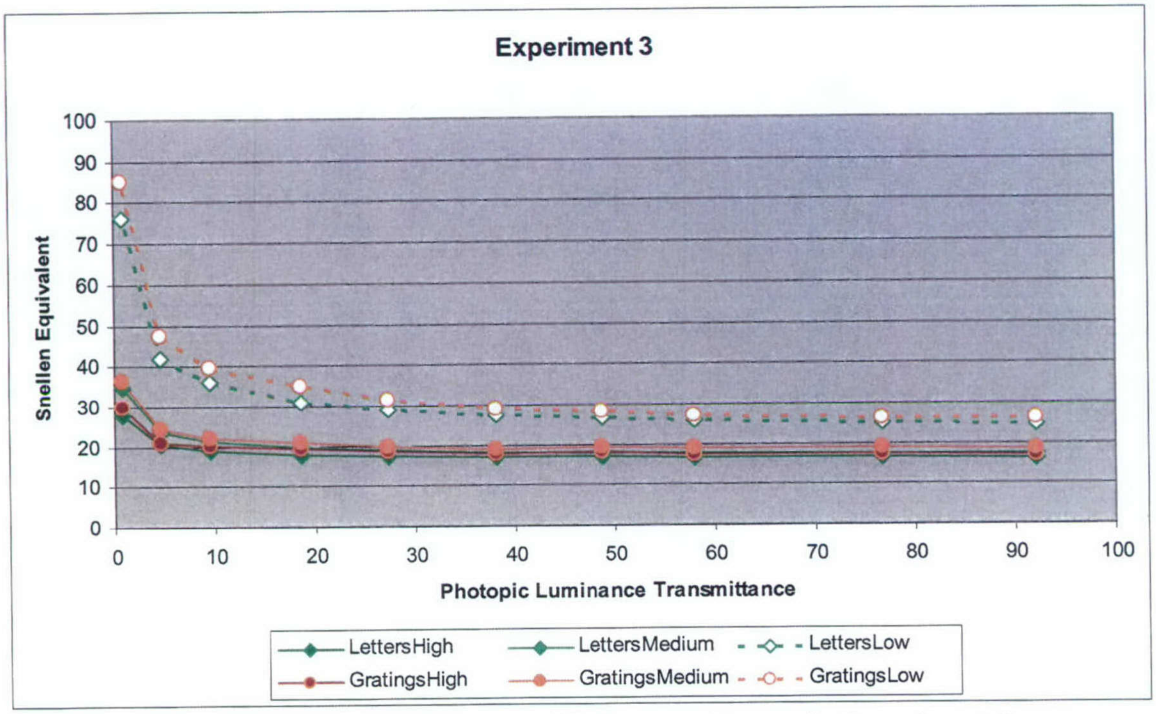


Figure 3.2 The effects of task, contrast and ND transmittance in Experiment 3.

A common question about LEP is how much transmittance is required to maintain acuity. The answer clearly depends on contrast. Contrast acuity slopes were computed between each ND filter and clear for each participant in each stimulus and media condition. Sequentially testing for a slope difference between adjacent ND filters, a statistically reliable break was found between 40% and 30% for the low contrast letters {$t(53)= 2.281$; $p= .027$} and low contrast gratings {$t(53)= 3.147$; $p= .003$}. For medium contrast stimuli, the break was between 40% and 30% for the letters {$t(53)= 2.919$; $p= .005$} and between 30% and 20% for the gratings {$t(53)= 2.254$; $p= .028$}. For the high contrast stimuli, the break was between 20% and 10% for both the letters {$t(53)= 3.917$; $p< .001$} and gratings {$t(53)= 3.356$; $p= .001$}. Only for the medium contrast stimuli was there an elbow advantage for Regan letters over gratings.

Consistent with the previous Experiments, acuity depended upon the media; $F(1.924, 32.713)= 55.732$; $p< .001$. Orthogonal comparisons revealed that paper was worse than the two monitors {$F(1,17)= 68.921$; $p<.001$} and that the LCD monitor was better than the CRT {$F(1,17)= 41.000$; $p<.001$}. The media differences increased as contrast was reduced; $F(2.049, 34.832)= 56.371$; $p< .001$. The media differences also increased as ND transmittance was reduced; $F(3.884, 66.030)= 3.474$; $p= .013$. The media X contrast X ND transmittance interaction was also significant and is shown in Figure 3.4. As can be seen, the media differences were largely limited to the low contrast stimuli, especially in the low ND transmittance conditions.

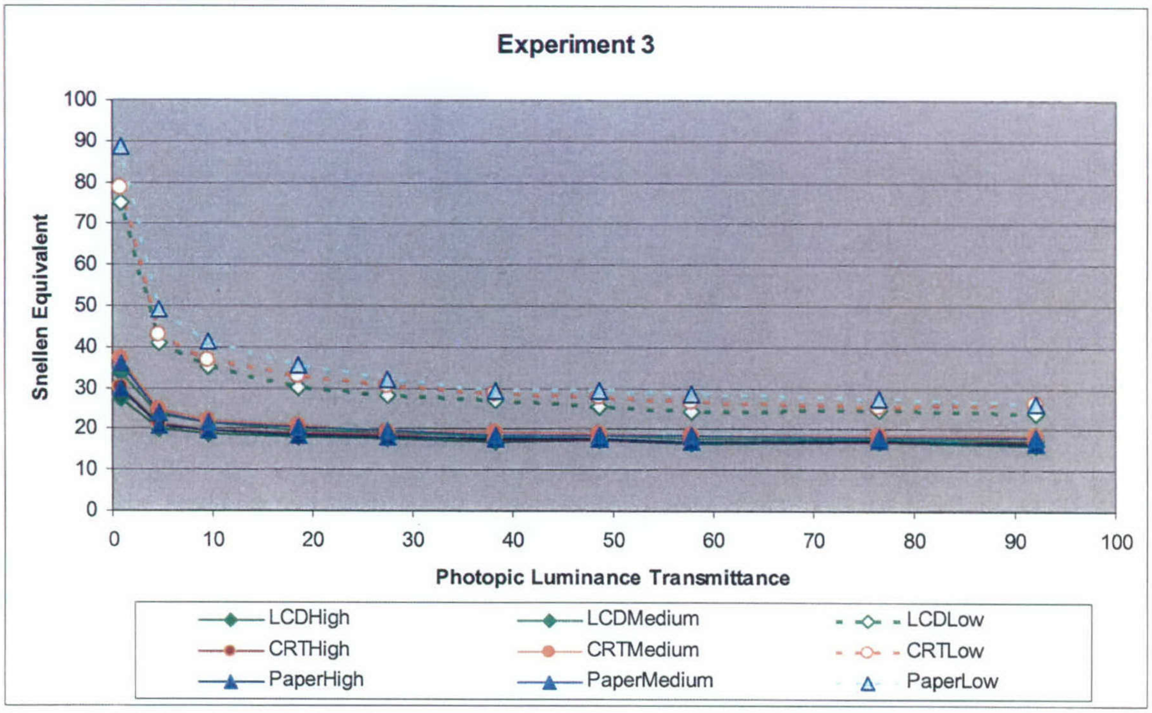


Figure 3.3 The effects of media, contrast, and ND transmittance in Experiment 3.

As in Experiment 2, acuity was a linear function of reciprocal contrast. Consequently plotting contrast sensitivity (acuity vs. 1/contrast) provides a simple way to see the impact of ND transmittance. Separate plots of contrast sensitivity for each stimulus task on each media is shown in Figure 3.4. The slope of the contrast sensitivity function is usually relatively flat until the ND transmittance drops below 40- 50%.

As a final way to represent the data, the mean Snellen Equivalents across participants were fit with the PLT of the ND spectacle and the contrast of the stimulus using TableCurve3D. Given the main effects of task (Regan letters and bar gratings) and media (LCD, CRT, and paper), each condition was fit separately. Two simple functions produced very high degrees of freedom adjusted r^2 values:

1/Snellen Equivalent= a + b*ln(PLT) + c/Contrast {mean r^2= .9933} and

1/Snellen Equivalent= a + b*ln(PLT) + c*ln(Contrast) {mean r^2= .9949}

The two plots did not perceptibly differ, but the first plot is presented in Figure 3.5 for compatibility with the contrast sensitivity plots. Figure 3.5 demonstrates two important points: the effects of the ND spectacles are very well fit and the important differences between the Regan letters and bar grating tasks and between the LCD, CRT, and paper media are at the low contrasts and low transmittance spectacle conditions.

Conclusions

The contrast sensitivity functions can provide a useful baseline against which to evaluate LEP spectacles. These samples are low in haze and high in clarity. For a given LEP, its contrast sensitivity function could be compared to the corresponding ND transmittance function. Any loss of photons is usually detrimental, but how does a given LEP compare after holding that loss constant? TableCurve3D can be very reliably used

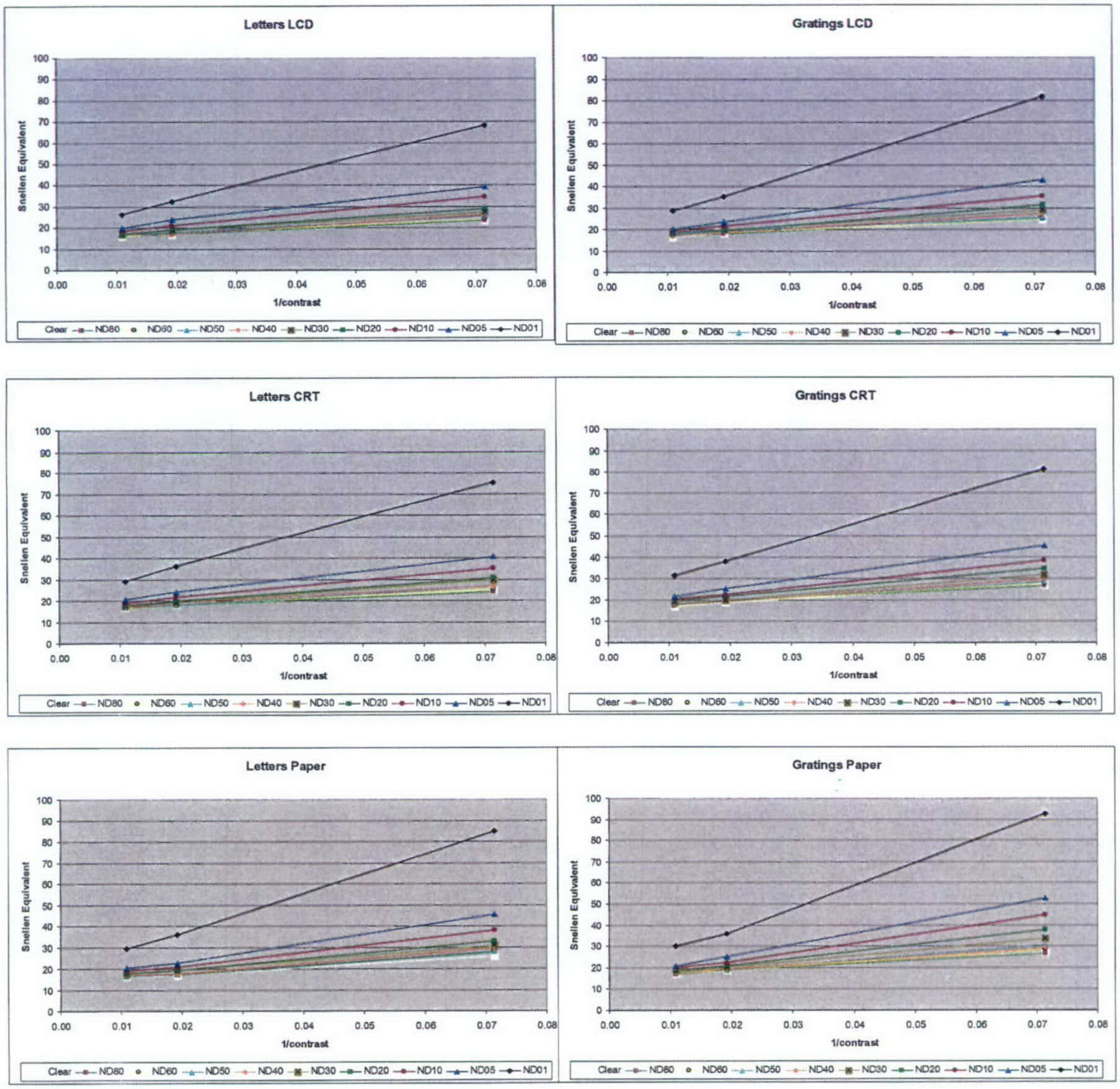


Figure 3.4 Contrast sensitivity for the stimulus tasks and media of Experiment 3.

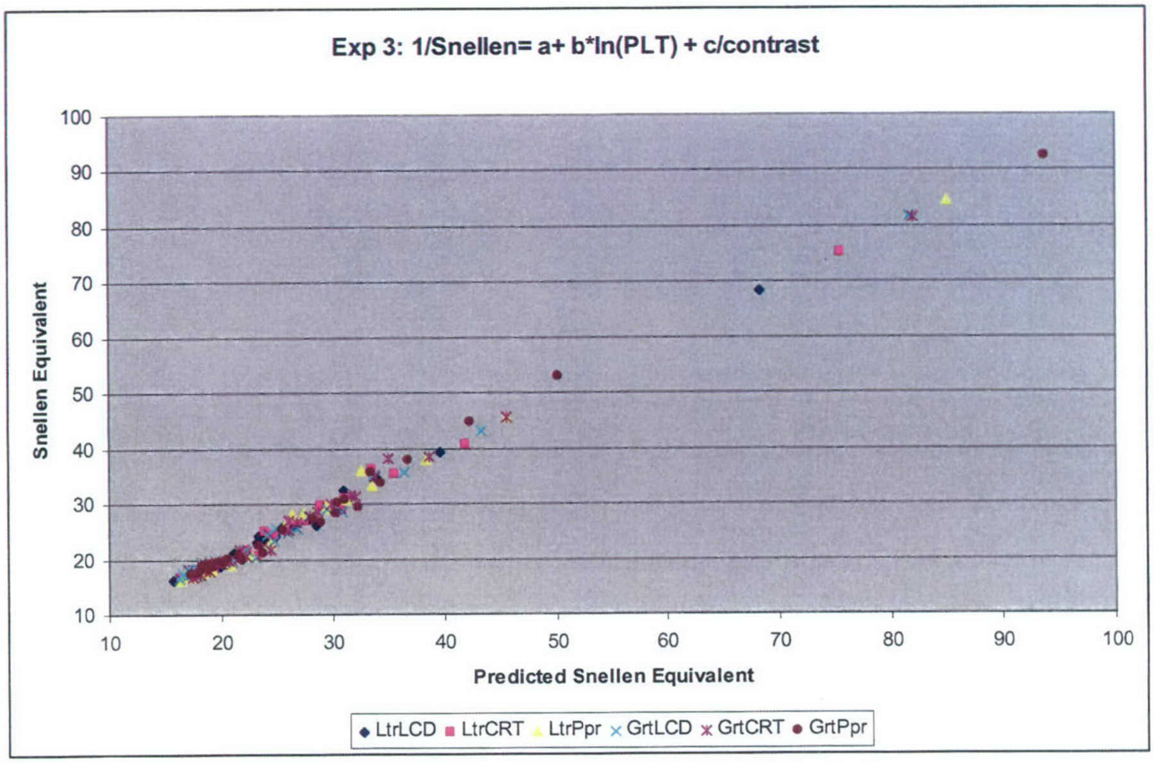


Figure 3.5 TableCurve3D fits for the Experiment 3 Snellen Equivalents.

to predict the best estimate of contrast acuity given low haze and high clarity.

Again, there was a Regan letter advantage over bar gratings, but both tasks proved very sensitive and reliable in terms of generating the contrast sensitivity functions across ND transmittance and media. The slight advantage of the LCD monitor over the CRT and of both monitors over paper is striking. Both monitors were new for the experiment, so alignment of the CRT guns should not have been a problem. Perhaps the poorer acuity for the paper stimuli could have been due to glare. Recall that the LCD and CRT monitors had hoods to block overhead, ambient light. Daytime cockpit conditions may "wash out" an LCD or CRT display, but clearly the recent move of clinical tests of acuity in office/laboratory settings away from paper charts and onto LCD and CRT displays is worthwhile.

Experiment 4

Rationale

The goal of Experiment 4 was to separate the effects on contrast acuity of overall reduced retinal illuminance from the effects of selective filtering within the visible spectrum. One potential benefit is improved evaluation of LEP. We would also gain a better understanding of the relative importance of the three cones in determining photopic acuity.

Method

Participants.

Seventeen participants (8 males and 9 females) completed all six sessions for the PSY 1013 credits and $60 compensation as in Experiment 3. Their mean age was 19.4 years (range= 18- 26). An additional 5 participants were recruited from PSY 1013. One fell asleep during the first session and was not recruited for any subsequent sessions. Four others earned PSY 1013 credit for the first session, but declined to continue for pay. Specifically, two different participants volunteered for the first session in an attempt to complete the 18 participant design, but neither of them wished to continue for pay at the end of the semester. It should be noted that 11 of the 18 participants from Experiment 3 were recruited for Experiment 4 in order to provide reliability measures.

Design.

Experiment 4 was very similar to Experiment 3, except that there were 10 in-band, glass filters instead of 10 ND spectacles. Specifically, Experiment 4 was a 2 stimulus tasks (Regan letters and bar gratings) X 3 contrast (high, medium, and low) X 3 media (paper, LCD, and CRT) X 10 colored glass filters (described below) repeated measures design. The counterbalancing scheme within days, across days, and across participants was the same as in Experiment 3, but the two sets of five filters in Experiment 4 were HN10, BL25, RD27, RD35, & HN40 and GR08, RD10, HN25, YL50, & HN52.

Stimuli.

The stimuli were the same as those used in Experiment 3. As described in Experiment 3, circle calibration stimuli were used to equate the white backgrounds and low, medium, and high contrasts across the three media (paper, LCD, and CRT) as measured by a Minolta CS100A colorimeter. These stimuli were measured again with a Minolta CS100A colorimeter after Experiment 4 was complete. As shown in Table 4.1, there was a slight increase in luminance (Y) and a slight increase in green (y). It is possible that a change in the ambient fluorescent lighting could account for these shifts. The luminance increase was generally larger for the paper stimuli (perhaps due to fading over time) than for the LCD and CRT monitors.

Table 4.1 CS100A colorimeter values for Experiments 3 and 4.

6/18/2004 Before Experiment 3				
Paper	Y	x	y	Weber %
White	121	0.387	0.399	
Low	104	0.385	0.398	14.05
Medium	58.3	0.380	0.394	51.82
High	10.4	0.397	0.400	91.40
LCD	Y	x	y	Weber %
White	122	0.391	0.399	
Low	105	0.385	0.401	13.93
Medium	58.2	0.380	0.396	52.30
High	10.3	0.397	0.398	91.56
CRT	Y	x	y	Weber %
White	122	0.387	0.398	
Low	105	0.383	0.398	13.93
Medium	58.6	0.380	0.395	51.97
High	10.2	0.399	0.400	91.64

6/2/2005 After Experiment 4				
Paper	Y	x	y	Weber %
White	127	0.385	0.404	
Low	111	0.385	0.406	12.60
Medium	61.2	0.383	0.400	51.81
High	10.0	0.396	0.407	92.13
LCD	Y	x	y	Weber %
White	126	0.394	0.407	
Low	109	0.390	0.406	13.49
Medium	59.2	0.384	0.404	53.02
High	10.5	0.405	0.418	91.67
CRT	Y	x	y	Weber %
White	123	0.391	0.404	
Low	108	0.386	0.405	12.20
Medium	58.7	0.390	0.409	52.28
High	10.6	0.404	0.415	91.38

The circle calibration stimuli were scanned with an Ocean Optics USB2000 spectrophotometer in two modes (OOIBase32 Platinum and OOIIrad). The raw values were interpolated to integer nanometer values between 340 and 1032 nm. The two modes produced highly correlated scans across the 12 circle calibration stimuli (mean r^2= .995, range= .979- .998), but different absolute raw scores due to different integration times. The OOIRad scores were transformed to the same scale as the OOIBase32 Platinum counts and the two scans were averaged for each of the 12 circle calibration stimuli. The calibration stimuli were also scanned with a PR1980B spectrophotometer. The raw scans are shown in Figure 4.1. Two global aspects of the raw scans are notable. First, the paper stimuli scans were very similar to the LCD stimuli scans. Instead of the paper stimuli being broadband, both stimuli had very similar peaks (436, 488, 544, 587, and 611 nm for the paper stimuli versus 436, 488, 546, 587, and 612 nm for the LCD stimuli). In order to distinguish between the reflectance of the paper and the power spectrum of the fluorescent lights, the Minolta flat, white reflectance standard (CSA21) was also scanned under the same illuminant conditions as the "white" paper. As can be seen in Figure 4.2, the power spectra for the "white" paper and the CSA21 are virtually identical (r^2= .9967). The fluorescent tubes in the lab (cool white) are intentionally "spikey" in order to artificially reproduce daylight color temperature. The engineers of the Sony LCD and the fluorescent tubes, by coincidence, adopted similar approaches. The second notable difference is between the spectral sensitivities of the USB and PR1980B spectrophotometers. Based on both photometers, the dominant wavelength peaks were between 611 and 626 nm. Compared to the peak(s) in that range, the OceanOptics USB readings were more sensitive than the PR1980B around the 545 nm peaks, but were less sensitive for short and long wavelength peaks (436 and 706 nm, respectively). The correlations between the USBMean and PR1980B scans were decent for the white background and low and medium contrasts (mean r^2= .860, range= .912- .805), but were disappointing due to restricted range for the high contrasts (mean r^2= .366, range= .460- .215).

In order to obtain best estimate spectra, each of the USB and PR1980B scans were first normalized to the CS100B Y values. Within the common range (370- 730 nm limited by the PR1980B) the average of the USB and PR1980B scans were computed for

each of the 12 circle calibration stimuli. The available USB values were used outside the common range (360- 370 nm and 730- 830 nm). Figure 4.3 presents the 12 best estimate spectra. Since none of the stimuli contained very much energy outside of the 400-700 nm range that is the range shown.

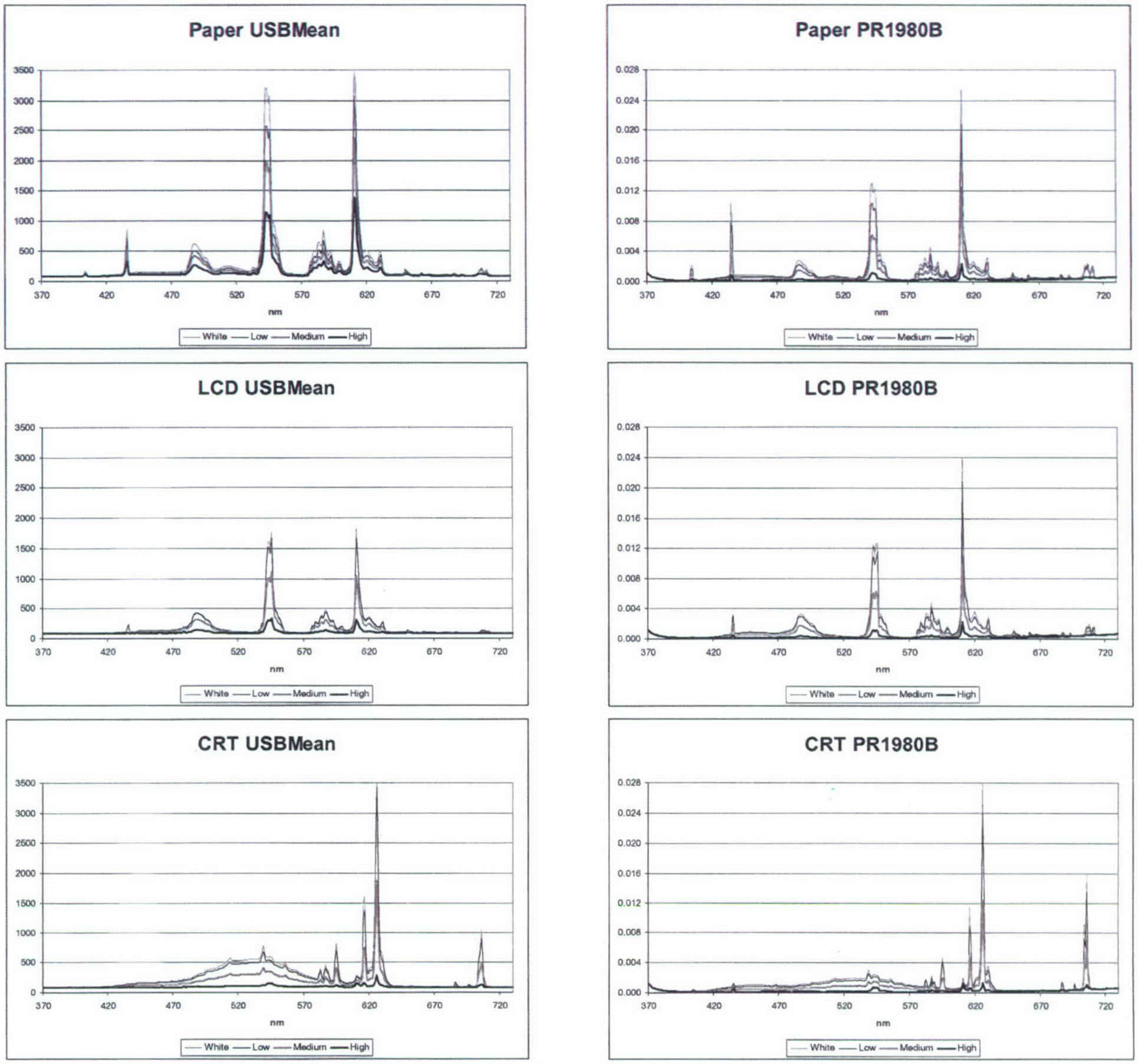


Figure 4.1. Raw USBMean and PR1980B scans of the four contrasts for each of the three media.

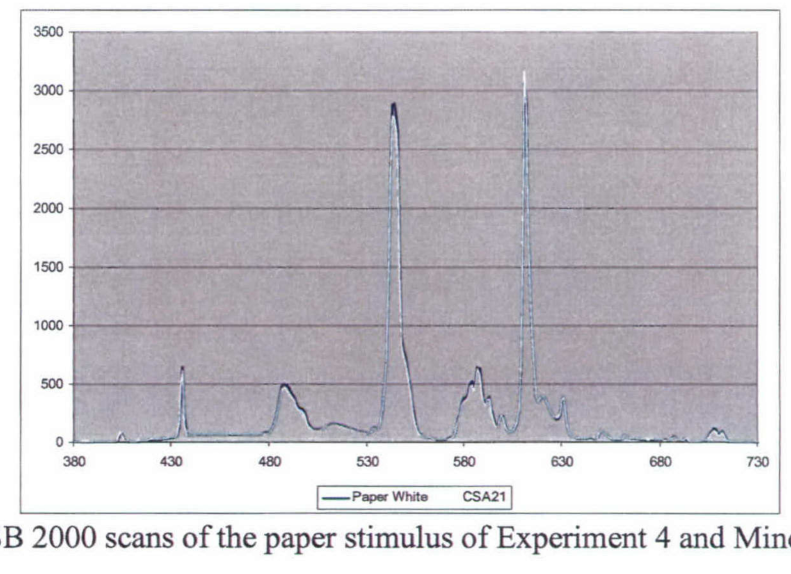


Figure 4.2 USB 2000 scans of the paper stimulus of Experiment 4 and Minolta

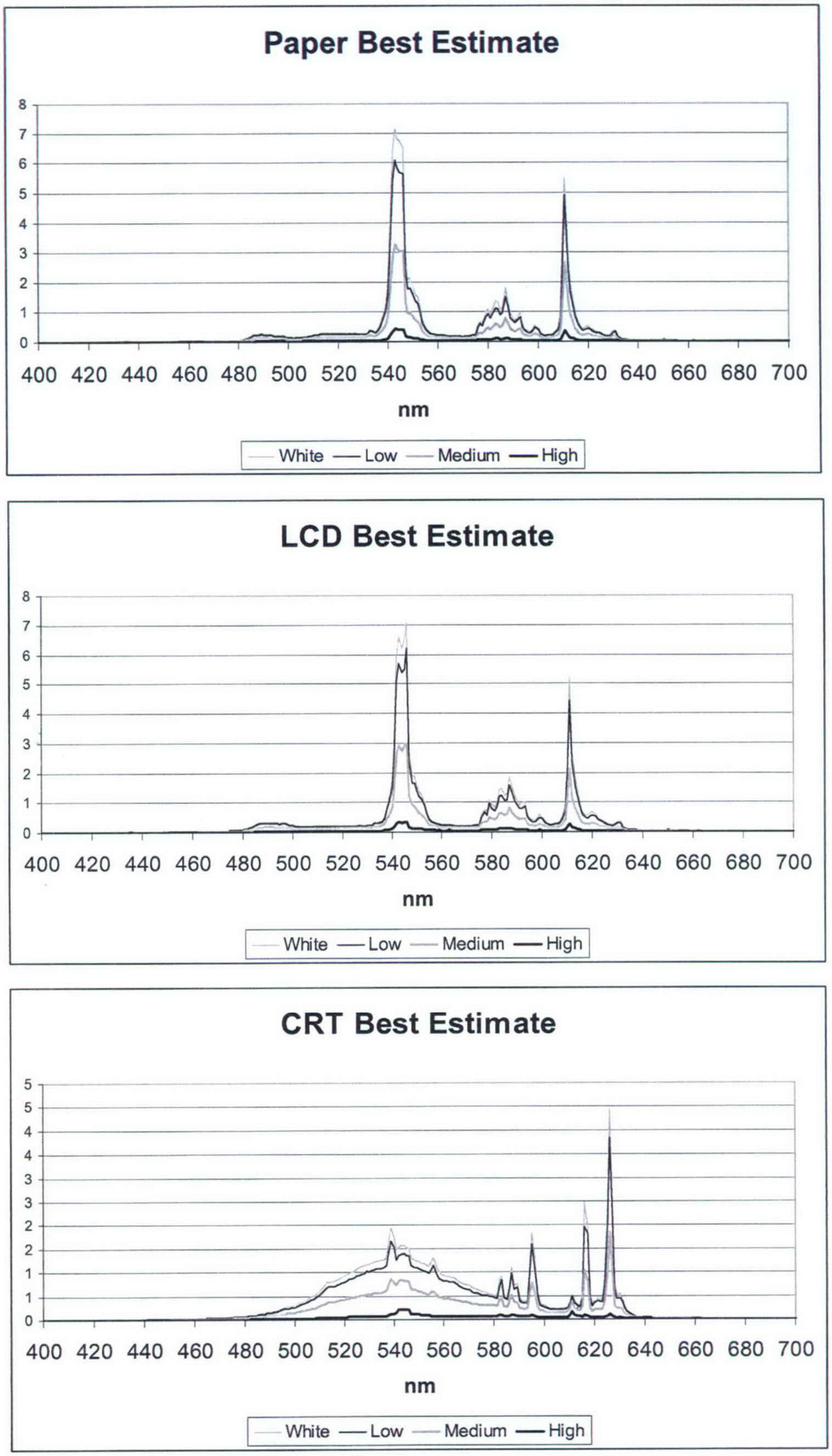


Figure 4.3 Best estimate scans of the 12 circle calibration stimuli in Experiment 4.

Apparatus.

The only important difference between Experiments 3 and 4 was that 10 ND spectacles were used in Experiment 3 and 10 colored, glass filters were used in Experiment 4. Based upon availability and html spectra on the website, a total of 16 4.25" X 2.00" Hoya colored glass filters were purchased from Newport Industrial Glass Works by the grant. The size of the filters was specified in order to mount them in vented, welder's goggles. This eliminated the ambient light and back-reflections of Experiment 3. Hoya glass was selected, because it's high optical quality and because it is used for the filter of the F15 MFCD. As with the Experiment 3 lenses, the Experiment 4 colored, glass filters were measured with a Cary5, Hazegard+, and Humphrey LA360. Of the 16 purchased filters, 10 were selected for Experiment 4. As can be seen in Table 4.2, their PLTs were moderate (a bit less than 10% to a bit over 60%). Table 4.2 also shows their high optical quality (maximum haze= .15% and minimum clarity= 99.6%). Figure 4.4 shows their transmittance spectra relative to the cone sensitivity estimates of Stockman et al. (1999, 2000). As can be seen in the figure, four of the filters were ND, four were high pass filters selected to vary the cut-off with respect to the l- and m-cones, one favored the m-cone, and one favored the s-cone. While ignoring PLT, Figure 4.5 shows their chromatic transmittance with respect to CIE xy space.

Exp 4	Hoya	Carey5					Hazegard+			LA360
Id	Id	PLT	x	y	z	SLT	%Trans.	Haze	Clarity	Visible%
HN10	ND3	12.3	0.316	0.318	0.366	12.194	12.40	0.10	99.8	13
HN25	ND25	27.4	0.317	0.332	0.351	26.562	27.80	0.05	99.8	28
HN40	ND40	40.1	0.314	0.325	0.361	39.467	40.80	0.06	99.8	41
HN52	ND50	50.8	0.311	0.322	0.366	50.555	51.70	0.07	99.8	52
RD10	R60	16.9	0.672	0.328	0.000	0.596	13.00	0.13	99.6	13
RD27	O58	32.0	0.618	0.382	0.001	2.725	27.00	0.09	99.7	26
RD35	O56	46.9	0.569	0.430	0.001	7.328	41.10	0.14	99.8	40
YL50	O54	65.4	0.514	0.483	0.004	18.351	60.40	0.15	99.8	62
GR08	G530	7.0	0.156	0.641	0.204	9.153	8.17	0.08	99.7	8
BL25	LB145	21.8	0.230	0.224	0.546	31.857	22.20	0.06	99.8	23

Table 4.2 Optical characteristics of the 10 colored, glass filters of Experiment 4.

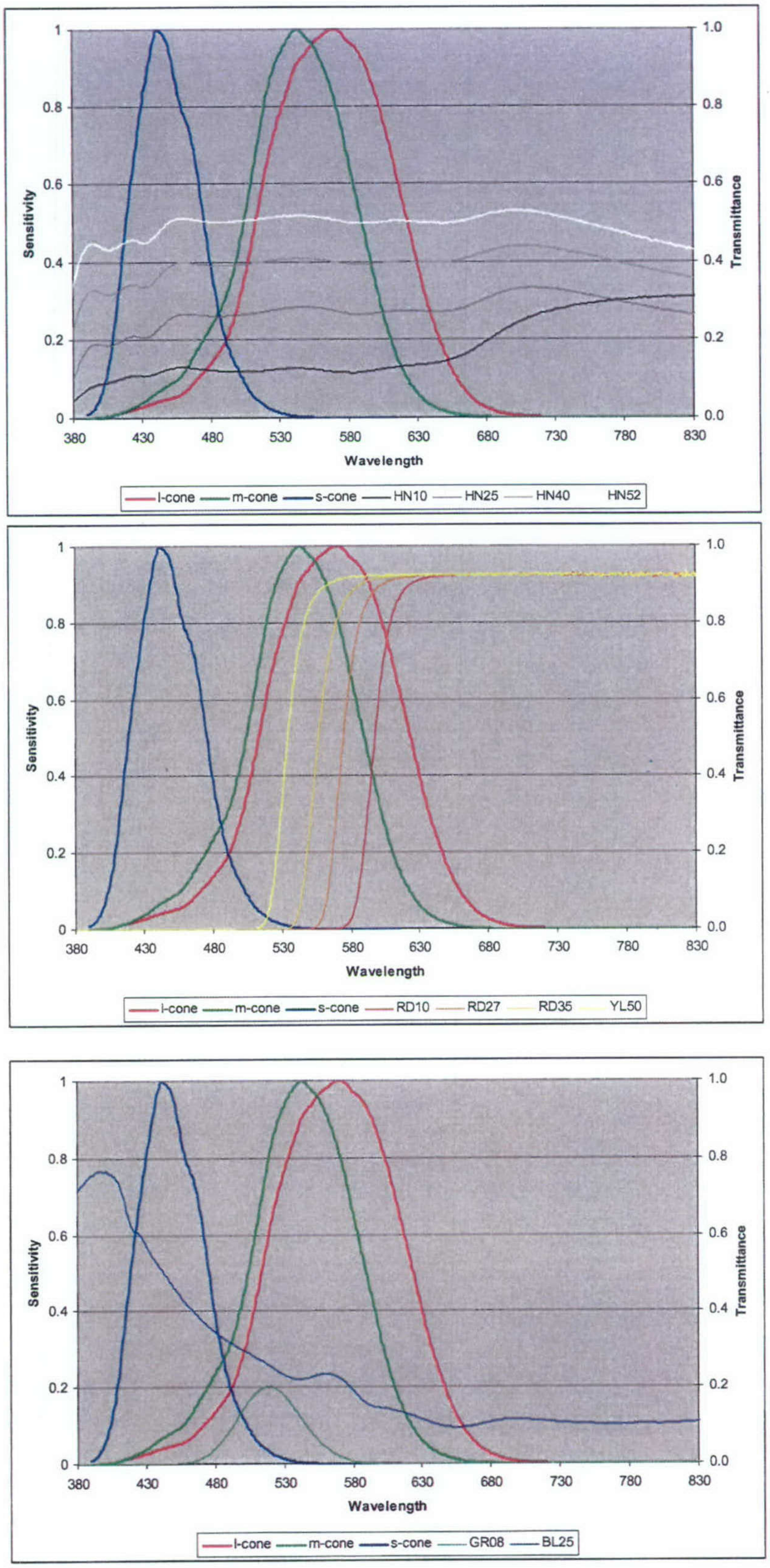


Figure 4.4 Transmittance spectra of the 10 colored, glass filters of Experiment 4.

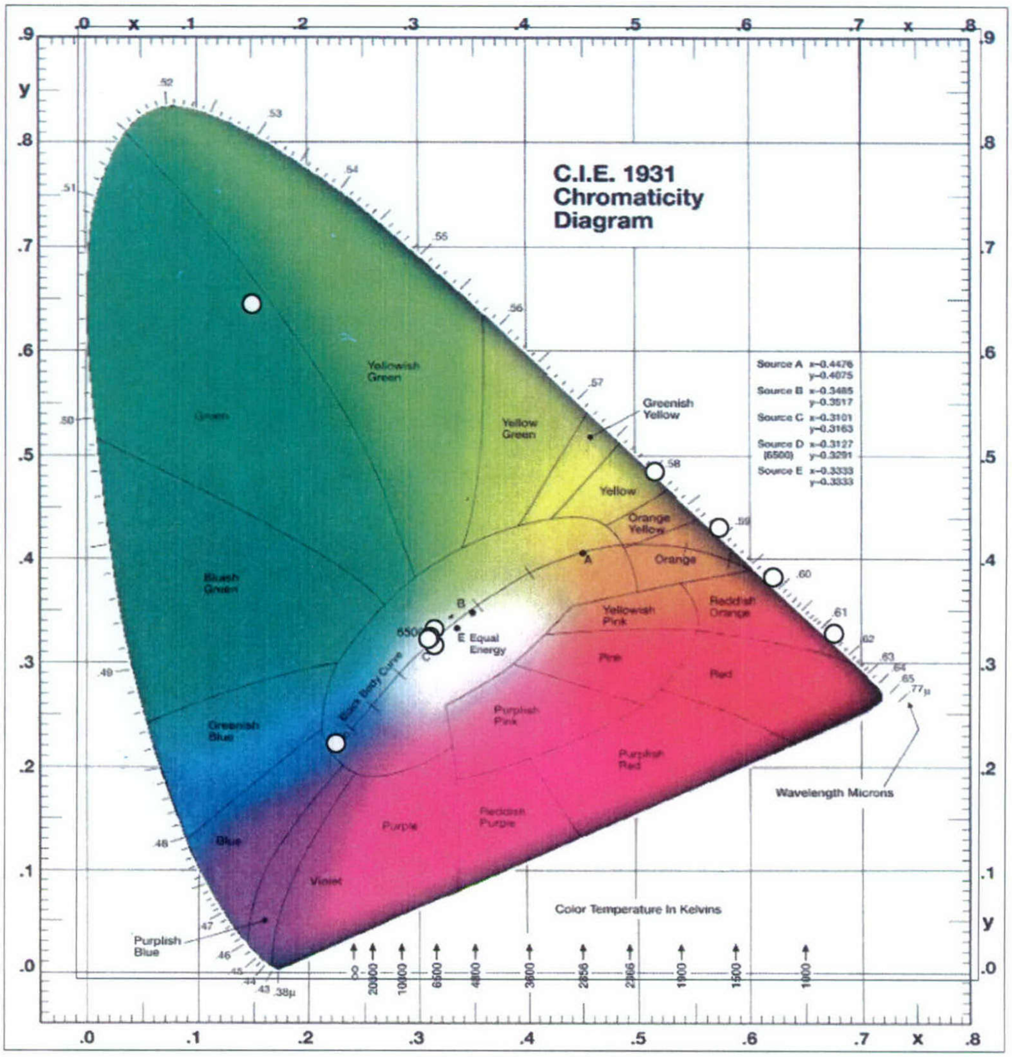


Figure 4.5 CIE plots of the 10 colored, glass filters of Experiment 4.

Procedures.

The procedures were the same as in Experiment 3, but there was no need for any participant to shield ambient light.

Results

The power spectra of the sources were convolved with the filter absorption spectra to obtain effective retinal spectra. In turn, these spectra were convolved with the photopic, scotopic, l-cone, m-cone, and s-cone efficiency curves. For the background, the ratio of the sum compared to the unfiltered weighted sum provides an efficiency curve-specific way to compare the filters in terms of transmittance for each media. Weber contrasts based on the photopic, scotopic, l-cone, m-cone, and s-cone efficiency curves were also computed for each contrast for each media through each filter.

For ease of exposition, the filters were rank ordered by their background photopic value in the Snellen Equivalents spreadsheet. This rank order was the same as for the

Cary5, except for a reversal of RD10 and BL25. These Snellen Equivalents were analyzed in a 2 (task: Regan letters and bar gratings) X 3 (contrast: high, medium, and low) X 10 (colored Hoya filters) X 3 (media: LCD, CRT, and paper) repeated measures ANOVA. Consistent with the results of Experiment 3, Regan letter acuity was better than for bar gratings {$F(1, 16)= 12.558$; $p = .003$}, reduced contrast hurt acuity {$F(1.023, 16.366)= 186.120$; $p< .001$}. Unlike Experiment 3, the Regan letter advantage did not significantly vary with contrast; $p= .176$. Experiment 4 included the 10 colored filters that varied in transmittance and spectral selectivity. These differences (especially reduced photopic transmittance) hurt acuity; $F(3.622, 57.946)= 59.271$; $p< .001$. As in Experiment 3, the effect of filter increased as contrast was reduced; $F(3.778, 60.454)= 38.163$; $p< .001$. Unlike Experiment 3, the effect of filter did not interact with the Regan letter advantage over bar gratings ($p= .286$) and did not enter into a three-way interaction with task and contrast ($p= .133$). It should be noted that the range of photopic transmittances was reduced in Experiment 4 compared to Experiment 3 in order to focus on spectral selectivity. The Snellen Equivalents for each of the 10 filters at each contrast for each of the tasks is shown in Figure 4.6.

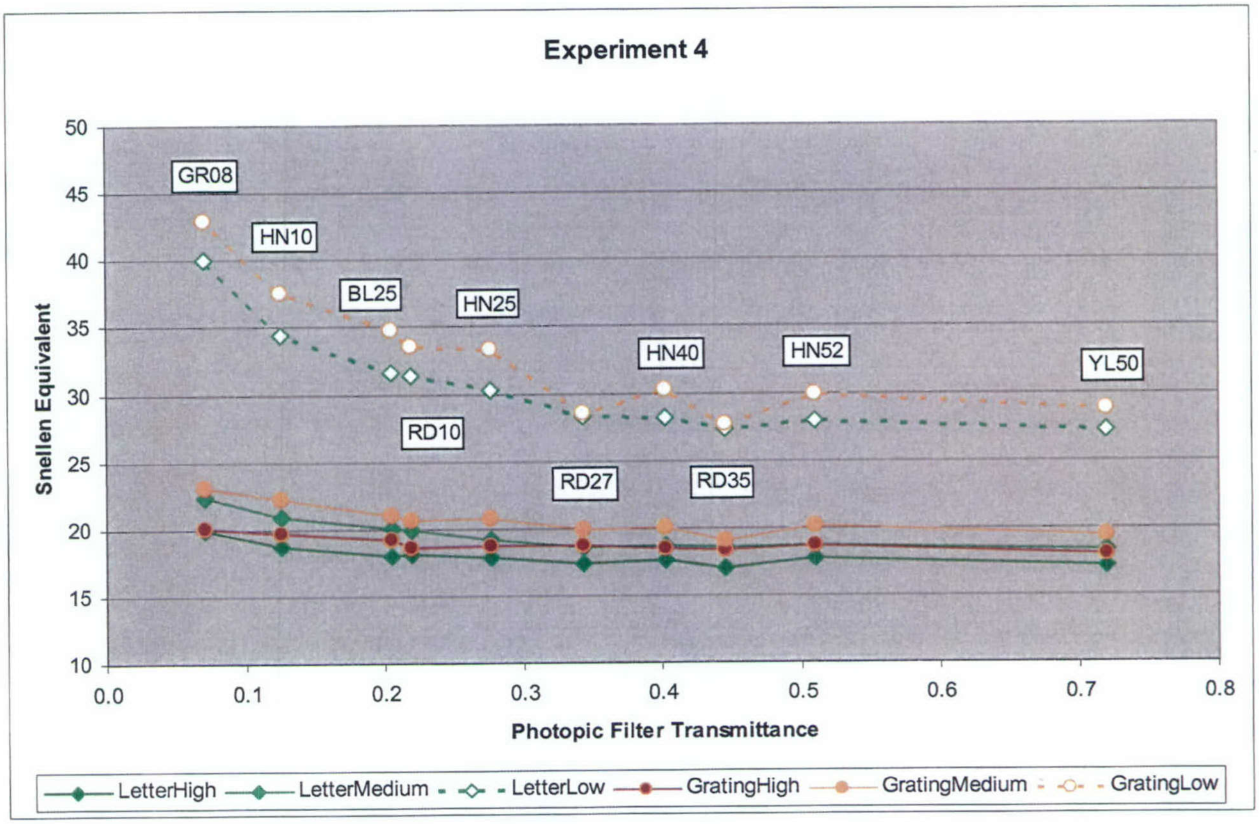


Figure 4.6 Snellen Equivalents for the stimuli in Experiment 4

Consistent with the previous Experiments, acuity depended upon the media; $F(1.814, 29.018)= 61.096$; $p< .001$. Orthogonal comparisons revealed that paper was worse than the two monitors {$F(1,16)= 14.352$; $p=.002$} and that the LCD monitor was better than the CRT {$F(1,16)= 70.416$; $p<.001$}. The media differences increased as contrast was reduced; $F(1.632, 26.108)= 67.454$; $p< .001$. The interaction between

media and filters only approached significance {F(6.235, 99.755)= 1.880; p= .089}, but the media X contrast X filter interaction was significant {F(6.498, 103.976)= 2.522; p= .022} and is shown in Figure 4.7. Note that the low contrast Snellen Equivalents for RD10 (transmittance= .219) differed widely between the paper and monitor media.

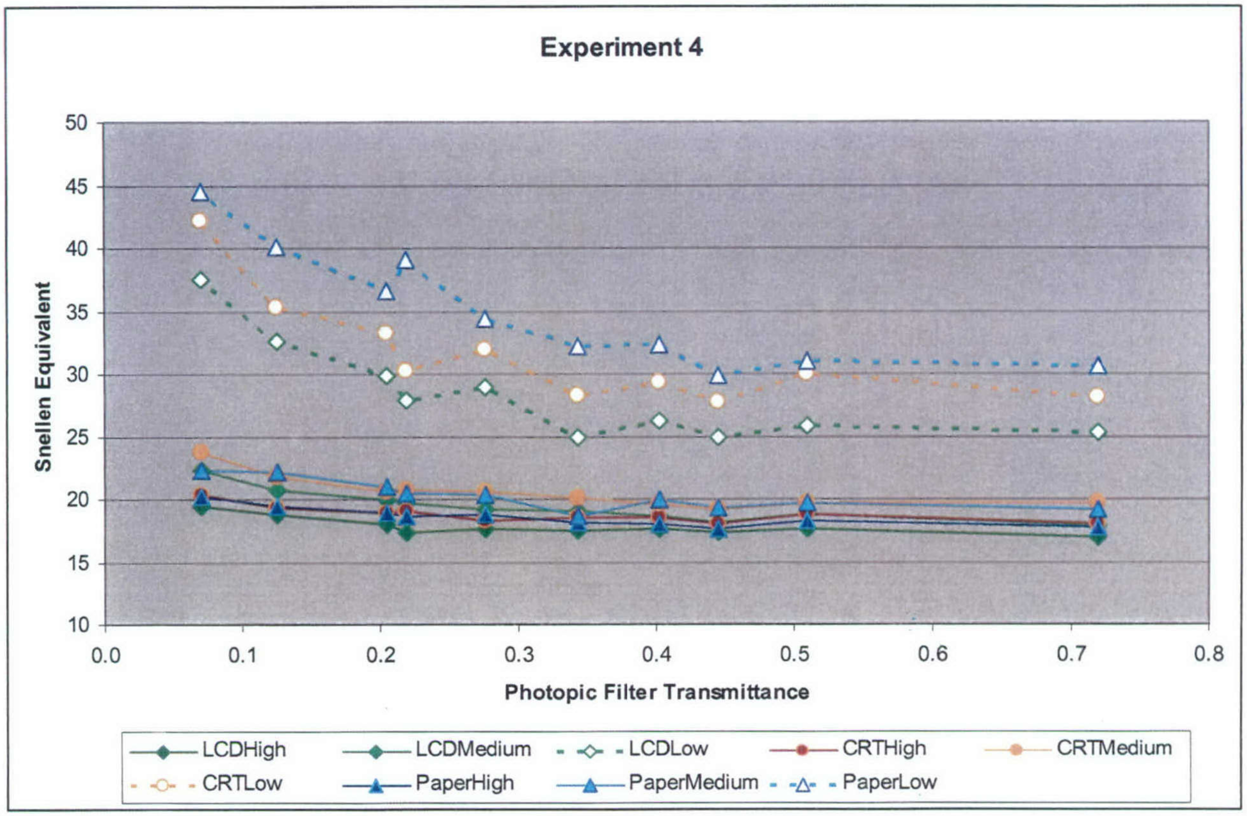


Figure 4.7 Effects of filters, media, and contrast in Experiment 4.

The computed transmittance and Weber constants were entered into TableCurve3D to fit the Snellen Equivalent data of Experiment 4. The best predictors were photopic filter transmittance and photopic Weber contrast. As in Experiment 3, the equation used to fit the data was

1/Snellen Equivalent= a + b*ln(PLT) + c/Contrast

The mean degrees of freedom adjusted r^2 was a bit lower, but was still very good (.978). Separate fits were performed for the two tasks (Regan letters and bar gratings) and three contrasts (high, medium, and low). The predicted and actual Snellen Equivalents are shown in Figure 4.8. The black points, line, and equation are for the four neutral filters. Note that the best-fitting line has almost perfect unit slope. The neutral filters should have unit slope, because they achieve their photopic measures across the visible spectrum. The filters that varied from l-cone to m-cone cutoffs are shown in red and yellow markers, line, and equation. Note that the slope is only slightly above 1.0. The filter that was mainly based on the m-cones is coded as green. Note that its slope is less than 1.0. The photopic sensitivity curve ($V(\lambda)$) is fit by the l-, m-, and s-cone sensitivity curves by .631, .392, and -.029 beta weights, respectively. The l- and m-cone weights are consistent with the greater number of l–cones than m-cones. The negative beta for the s-cones is due to historical measurement problems at short wavelengths. At least in terms

of contrast acuity, these data suggested that the m-cones have been underestimated and the l-cones have been over estimated. The s-cone filter data fit almost exactly on the line, providing no evidence of increased acuity with "blue-blockers".

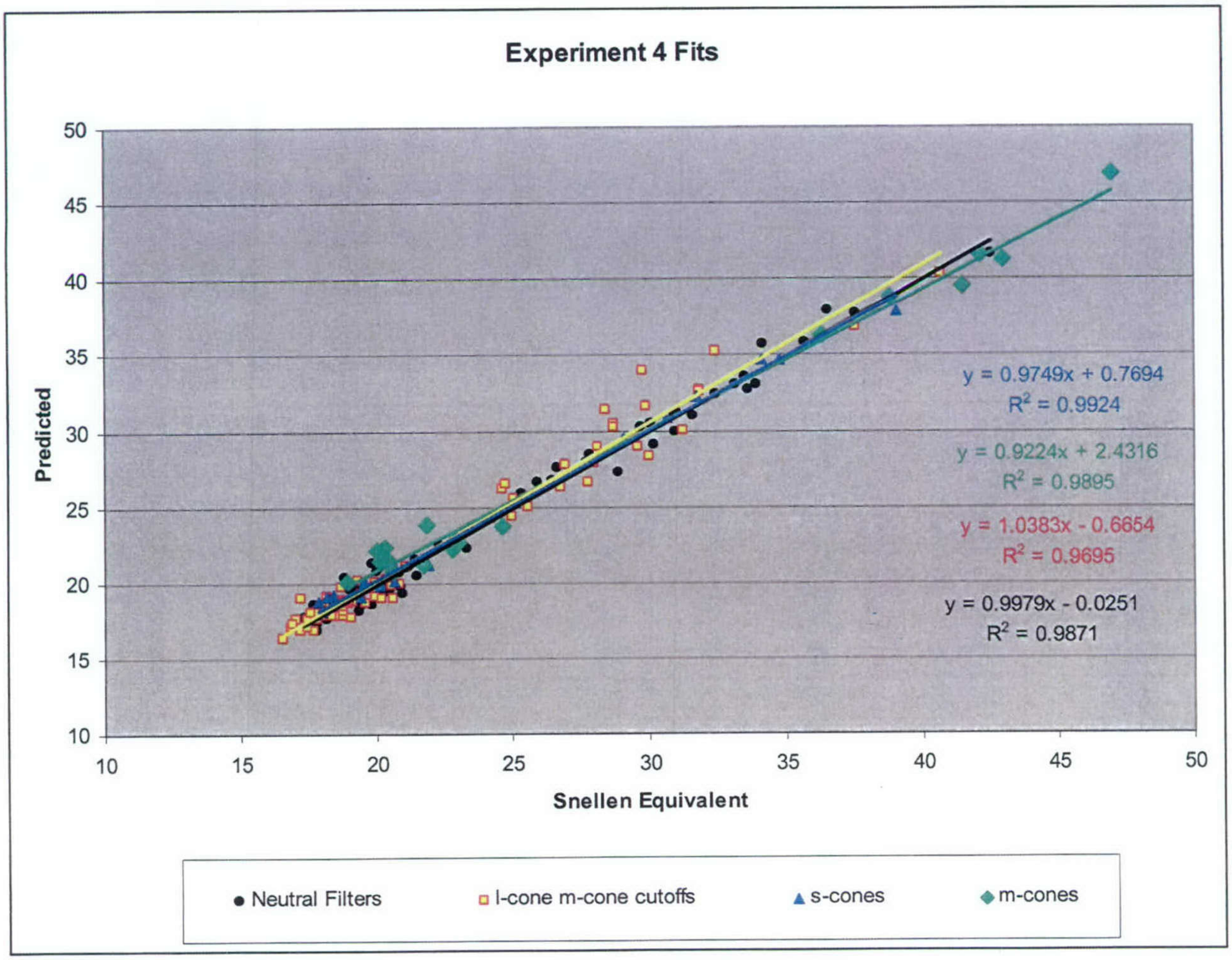


Figure 4.8. The Snellen Equivalent fits for the Experiment 4 data as a function of the type of filter.

Conclusions

Although different parameters are found with different stimulus tasks and media, acuity was well fit by ln(photopic transmission of the filter) and reciprocal photopic Weber contrast. By measuring the stimuli used relative to cone sensitivities, it appears that the fit could be improved by increasing the m-cone weight relative to the l-cone weight. The importance of measuring the stimuli was most apparent when considering the paper stimuli. Although the paper had a broad band reflectance, the fluorescent lights in the lab were very "spikey" in some parts of the visible spectrum.

Discussion

The most important conclusion for LEP evaluation is that the testing with low contrast stimuli is critical. In order to match across media, these experiments were limited to a minimum of an 11% contrast. AFRL/HEDO uses both the 11% and 4% contrast Regan charts. As for stimuli, AFRL/HEDO uses Regan letters and they were shown to have very high reliability and validity in this research. AFRL/HEDO has also used bar gratings in evaluating LEP compatibility with NVGs. Bar gratings were the second most reliable stimuli in this experiment. Tumbling E stimuli are not recommended since they are not as sensitive. Landolt C stimuli and octagons might work with highly practiced observers in the lab, but the same problems encountered with PSY 1013 students might also occur in the field.

The issue of media is more complex. The LCD displays were consistently the best media in these studies. While there can be off-axis color shifts and drops in brightness, LCD displays should be considered for evaluating LEP. If the choice is made to use Landolt stimuli, octagons would be recommended. The only major concerns in the cockpit environment would be wash-out by the sun and ruggedization.

The ND functions of Experiments 3 and 4 can be used as a baseline against which to compare LEP. Are there any problems with the LEP that reduce acuity beyond the simple result of reduced transmittance? Overall, the photopic sensitivity function fit the contrast acuity data quite well. There were hints that function may slightly overemphasize the importance of l-cones and underestimate the importance of m-cones. While only a small effect in these data, the problem may be exacerbated by providing protection against some in-band laser threats.

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